

LME SUSCEPTIBILITY OF GALVANISED WELDED STRUCTURES OF HIGH STRENGTH STEELS

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Abstract Hot dip galvanizing is a very popular and well known process in corrosion protection of steel. However, very occasionally, cracks appear on structures when they leave the zinc bath. The responsible crack phenomenon appears to be liquid metal embrittlement. This phenomenon is already known for a long time, but it is still not yet fully understood. The lack of fundamental theoretical knowledge and the absence of accurate models to predict liquid metal embrittlement oblige engineers to set up extensive test programs to determine an area of process parameters in which safe design is guaranteed. A qualitative understanding of the various influencing parameters during galvanizing is necessary to explain the occurrence of liquid metal embrittlement. This knowledge is also helpful to design an experimental test set up and procedure for evaluating the influence of one parameter where the effect of other parameters should remain constant. This master thesis deals with the occurrence of liquid metal embrittlement when galvanizing welded high strength steels. This paper gives an overview of the most important process parameters and gives a short description of possible future experimental work.

Keywords liquid metal embrittlement, LME, welding, high strength steel

1 INTRODUCTION

Hot dip galvanizing is a process in which a zinc coating is applied on a steel specimen. This metallic layer, which is metallurgically bonded with the steel substrate provides an excellent protection against corrosion. The zinc coating is applied by immersing the steel in a bath of zinc (450°C / 840 F). Considering the large amounts of steel structures that fail due to oxidation, corrosion protection is of great economical interest. A zinc layer provides three levels of protection. The first is the physical barrier that separates the steel from oxidation agents. Another protection level is the galvanic protection. The zinc acts as a sacrificial anode that makes iron oxidation impossible when the Zn layer is damaged. A final level of protection is offered by the zinc oxides that cover defects in the zinc layer. These three levels of protection make galvanizing more advantageous than painting, which only offers barrier protection.

The hot dip galvanizing process was patented in 1837 [1] and became widely used during the 20th century. The first ASTM standard concerning galvanizing dates from 1928 (ASTM Standard A 123, currently listed as "Standard specification for zinc (hot-dip galvanized) coatings on iron and steel" [2]). Since then, standards, practices and guides have been developed to avoid significant problems due to the galvanizing process. Nowadays almost all problems occurring after hot dip galvanizing are found to be due to misunderstanding of those codes [2]. However, during the last decades, cracks in galvanized steel have been sporadically reported. Those cracks originated at flame cut edges, welds or heavily cold formed parts. Examination of the cracks showed that they occurred due to liquid metal embrittlement (LME). This phenomenon is also called liquid metal assisted cracking (LMAC) or liquid metal induced cracking (LMIC) or liquid metal induced embrittlement (LMIE).

Welds in galvanized structures have been found to severely increase the LME susceptibility. Using high strength steels in galvanized structures also seemed to be detrimental to avoid LME cracking. In this master thesis, the LME susceptibility of welded high strength steels (Q&T and TMCP) will be investigated.

2 LIQUID METAL EMBRITTLEMENT (LME)

2.1 Introduction to LME

The failure process during liquid metal embrittlement is not yet fully understood. Hence, lots of definitions and models have been proposed to define and explain the phenomenon [3]. One of those definitions describes liquid metal embrittlement as "a mechanism one in which the ductility of a solid metal is reduced

by surface contact with a liquid metal" [4]. Despite the lack of fundamental knowledge of the failure process, the relative importance of influencing process parameters has been mapped in various research projects.

Liquid metal embrittlement was found to require an embrittling agent (in particular, the liquid zinc bath), a normally ductile embrittled metal and a force field at the time and place of the embrittling contact [2]. Cracks that occurred after retaining the steel part from a zinc bath are always intergranular [5].

The embrittling process during hot dip galvanizing is governed by lots of parameters, each of which cause a modification in at least one of the four influencing aspects which are represented in figure 1. The first aspect is the mechanical and metallurgical condition of the steel. The second is the environment, e.g. composition and temperature of the zinc bath. The third aspect is the acting forces, both residual and external ones. The last aspect represents the influence of time, which refers to the immersion time.

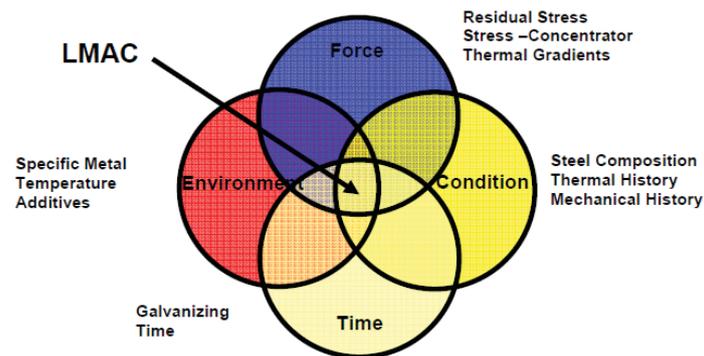


Figure 1. Aspects influencing LME [6]

2.2 Specificity of LME

Liquid metal embrittlement can only occur in particular combinations of solid and liquid metals. The solid should be sufficiently wetted by the liquid metal. Solid-liquid metal couples that form intermetallic compounds, usually do not show liquid metal embrittlement. The steel-zinc contact however is characterised by such compounds, as can be seen in figure 2. Research in specificity of liquid metal embrittlement showed that the Fe-Zn couple was not susceptible to liquid metal embrittlement.[7] Nonetheless the cracks found after galvanizing are clearly due to liquid metal embrittlement.

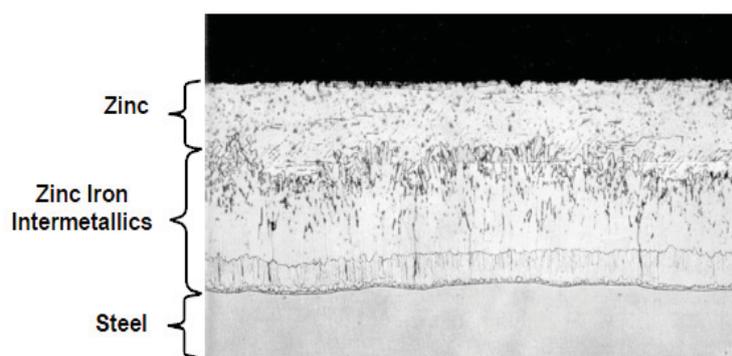


Figure 2. Typical galvanizing microstructure [2]

This seems to be contradictory, but can be explained when considering other elements apart from zinc that are used in a zinc bath. To obtain a smooth zinc surface after galvanizing, some elements are added to the zinc, amongst which are Pb, Sn and Bi. As can be seen on the EDX-analysis of a crack tip [6], the concentration of those elements at the crack tip has increased significantly compared to those in the zinc bath. These elements are known to sufficiently wet steel surfaces and thus show more liquid metal susceptibility compared to pure liquid zinc. They also have much lower melting temperatures than zinc.

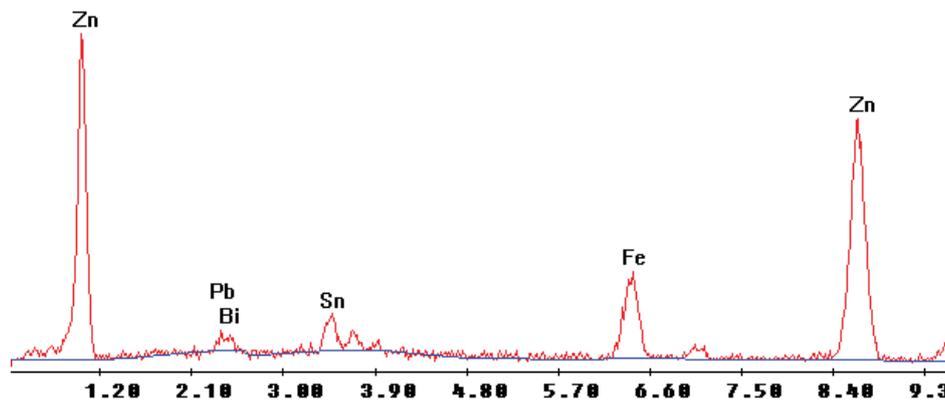


Figure 3. EDX analysis at crack tip [6]

2.3 Model for liquid metal embrittlement during galvanizing

Given the melting temperature and steel wettability of the afore mentioned additives, a model was proposed for cracking during galvanizing [2]. When the steel is immersed in the zinc, a reaction occurs between the steel and zinc, and intermetallic compounds are formed. The low melting temperature additives cannot participate and are banned from the reaction surface. Because zinc is consumed, the concentration of the additives near the steel surface increases and a thin layer is formed that separates the intermetallic compounds from the rest of the zinc bath. This layer prohibits uncontrolled growth of the intermetallic layers, what leads to a smooth surface.

However, when the liquid metal penetrates existing cracks, rejection of the afore mentioned additives is prohibited by the intermetallic layer that formed at the crack root. The liquid metal in the crack becomes trapped. The zinc continues to be consumed to form intermetallic compounds. A melting pool is formed in the crack and contains high concentrations of Pb, Sn and Bi which have not yet solidified because of their low melting temperatures. The remaining liquid metal is known to show a very high susceptibility to liquid metal embrittlement in combination with steel. The crack will propagate when enough stress is applied.

3 FORMER RESEARCH RESULTS

As mentioned before, the LME phenomenon is not yet fully understood. Theoretical insight of the metallurgical process is impeded by some factors. First of all, because of all the additives in the zinc bath, the growth of the zinc layer is not governed anymore by the simple binary Fe-Zn phase diagram. Secondly, different reactions take place at the same time: the wetting of the surface, dissolution of steel by zinc, isothermal solidification of intermetallic compounds, solid state diffusional phase transformations, and solidification of liquid zinc alloy. Moreover, those reactions all have a high reaction speed [8].

Due to the lack of fundamental understanding, one cannot make theoretically based predictions regarding the exact influence of process parameters. This means that extensive testing is necessary to confine the limiting design properties that should not be exceeded in safe design.

3.1 Stress-strain behavior in liquid zinc

The first experimental programs about LME during galvanizing were started in the early eighties. Kikuchi investigated the LME susceptibility of steel by doing tensile tests on unnotched specimens in a zinc bath [9]. Figure 4 shows the resulting stress/strain curves. As can be seen on this figure, the steel shows a loss of some of its mechanical properties (as stiffness and strength). When tensile tests are done in the zinc bath, the resulting stress-strain curve follows the corresponding curve measured on a specimen tested in air at the same temperature. However when a certain threshold stress/strain is reached the curve drops down, the steel shows sudden fracture. This threshold stress always exceeds the yield stress. This observation cannot be extrapolated to other metal couples showing LME [10]. In actual structures, stress concentrations such as grain boundaries, second phase particles and notches are capable of producing localised plastic deformation sufficient to cause LME cracking, and general plasticity is not essential [11]. When no brittle fracture occurs, all mechanical properties recover when cooled to room temperature after galvanizing [12].

Not only strength (YS and UTS) and stiffness decrease when tested at elevated temperatures. Other research programs also found a detrimental effect on toughness [12][13]. However, all properties fully recover after galvanizing (when no LME has occurred).

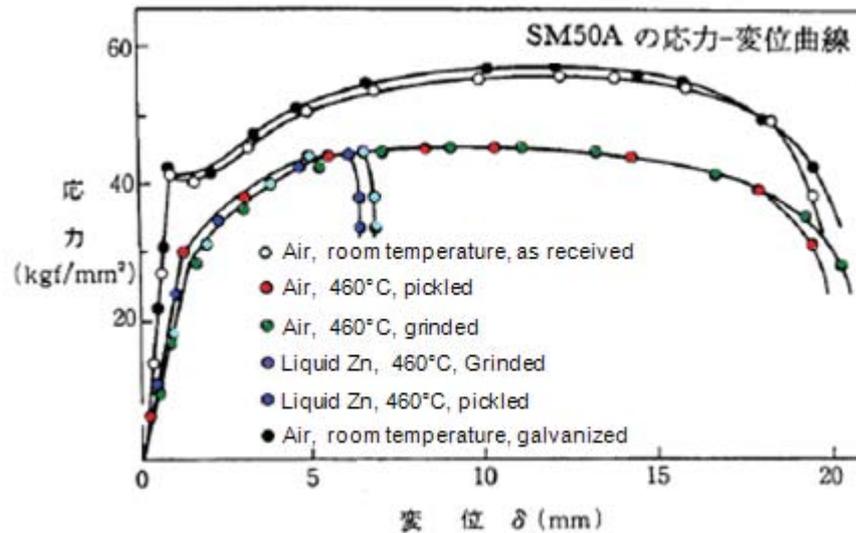


Figure 4. Stress/strain curves obtained from tensile tests [9]

3.2 Stresses induced during the galvanizing process

As mentioned before, stress is a predominant factor in LME initiation. Hence it is essential to know and understand the processes which cause stresses that can trigger LME initiation. Between dipping in the zinc bath and withdrawal, the temperature of the steel changes from the ambient temperature above the bath to the liquid zinc temperature and then back again. This temperature variation causes thermal gradients in the steel which induce stresses. The level of these stresses is a function of several parameters, of which the most important ones are [8]: the dipping and withdrawal speed and angle, the structure geometry and the bath composition (influence on the heat transfer rate at the solid liquid contact surface [2]). Preheating the steel can lower thermal gradients, as can lowering the bath temperature.

These stresses can accurately be modeled with finite element simulations [12]. The results however are only valid for one combination of the influencing parameters described above and the simulations are rather time consuming. Nonetheless such simulations can give insights in the relative importance of the parameters. The European test program "Failure mechanisms during galvanizing" [12] did some extensive research on those parameters.

3.3 Stresses in galvanized structures induced by manufacturing

Several manufacturing processes are known to introduce residual stresses in structures. The stresses result from cold working or thermal processes (e.g. flame cutting and welding). Residual stresses can be detrimental regarding to LME.

3.4 Hydrogen embrittlement

In industrial galvanizing, the structures are chemically cleaned by pickling and fluxing before entering the zinc bath. These processes are known to introduce significant hydrogen concentrations on the surface (figure 5). This might increase the susceptibility to hydrogen embrittlement during galvanizing. However all test programs regarding hydrogen embrittlement concluded that the H concentrations didn't cause cracking except for steels with tensile strengths > 800 MPa [12][13]. These tests were performed with smooth steel specimens. However when manufacturing processes result in high local hardness, hydrogen embrittlement can become a problem. This local hardness can be induced by welding, flame cutting or severe cold working. Especially the welding process is known to introduce hydrogen microcracks, when executed in suboptimal conditions [14]. It is recommended not to exceed hardness values above a certain threshold

(± 300 HV) [15],[2]. Several guides and standards have been written, e.g. EN 1011-2, that can be followed in order to avoid hydrogen induced cracking [15].

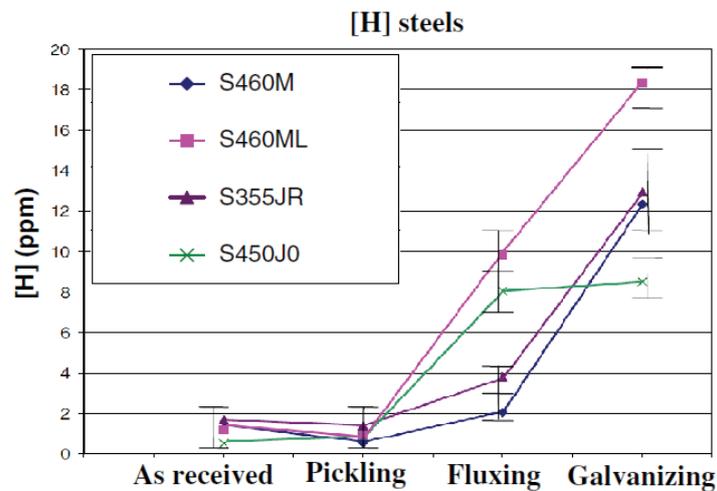


Figure 5. Evolution of hydrogen concentration on the steel surface[16]

3.5 Influence of steel microstructure

The microstructure of the steel surface also has a strong influence on the liquid metal susceptibility. Some researchers linked the susceptibility to the carbon equivalent value (CEV) which is generally used in welding practices. They proposed a CEV limiting value that should not be exceeded in safe design [14]. This value however is no “condition sine qua non” to allow safe design, as there are lots of other influencing parameters.

Not only the overall steel composition is important, also the metallurgical structure of the steel (e.g. grain size, apparent phases,...) is decisive for liquid metal embrittlement. This metallurgical state of the surface can be severely altered by welding processes. Therefore welding parameters as cooling rate and welding material should be chosen carefully.

4 FUTURE WORK

The final goal of this thesis is to define a restricted area in which galvanizing process parameters can vary ensuring a safe design of high strength steel welds. Though the obtained results are, strictly taken, only valid for the used steels and zinc baths, extrapolating the results will certainly improve qualitative understanding in the behaviour of welded high strength steels in general.

In the test procedure, the welding of the steel will be simulated by imposing a temperature cycle on the test specimens. This cycle will result in a certain metallurgical state. This state will approach the one of the HAZ of the base material after an actual welding process in which the same temperature cycle is imposed.

After the welding simulations, the specimens need to be cleaned, before entering the zinc bath. When using different cleaning methods one can evaluate their influence, e.g. chemical cleaning which can cause hydrogen embrittlement versus mechanical cleaning methods like sand blasting.

To evaluate the LME susceptibility the specimens finally need to be stressed in a liquid zinc environment. The necessary equipment to perform traditional tensile tests in a zinc bath, is currently not available at the laboratory. However there are three alternative solutions

- 1) Tensile tests can be done in cooperation with the university FH Esslingen, Germany
- 2) A simple small scale test setup can be designed that allows testing at the galvanizing company Galvpower in Dendermonde, Belgium
- 3) The test specimens can be galvanized without implied stresses and can afterwards be tested with test equipment which allows testing at elevated temperatures. In this case, the testing temperature would be the one of the zinc bath.

5 ACKNOWLEDGEMENTS

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