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SciVerse ScienceDirect
Procedia Engineering 40 (2012) 241 – 246
Procedia Engineering
www.elsevier.com/locate/procedia

Steel Structures and Bridges 2012

Post on the issue of safety of steel structures of hot dip galvanized structural components

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Abstract

Worldwide, the majority of newly built steel structures are protected against corrosion by hot dip galvanizing. The coating is applied by immersion of steel parts in molten zinc at a temperature around 450 °C. Components supplied for coating are characterized by the presence of residual stress inserted into them during their manufacture, from the rolling process, through the forming and welding, optionally through the subsequent straightening. During immersion in molten zinc are the parts exposed to a sudden uneven heating inducting some variable tension usually reaching the yield point of steel. In extreme cases, these effects lead to a disruption of the material integrity. The safety of the steel structures is one of priority questions to which should be found a reliable answer. Detailed knowledge of the stress state of steel exposed to uneven heating from the gradual immersion in molten zinc and of the changes induced in the structure of the material is essential for a thorough analysis of the issue in all the physical and metallurgical patterns and contexts and to formulate reliable conditions under which the risk of crazing relevant reducing the carrying capacity with the dip galvanized steel building components could be eliminated.

Keywords: uneven heating; variable tension; stress concentration; liquid metal assisted cracking

1. Hot dip galvanizing

In practice, hot zinc coating is applied by dipping of pre-treated steel parts in molten zinc with a temperature of approx. 450°C. Besides residual internal stress (introduced into the part during the whole process from the production of the blank up to straightening after welding) there are other important factors influencing the material characteristics of hot dip galvanized steel structural elements. During gradual immersion into molten zinc individual parts are exposed to contact with the molten metal and at the same time to abrupt uneven heating up causing other variable stress in them, which generally achieves the yield point of steel. In an

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doi:10.1016/j.proeng.2012.07.087

extreme case these effects may disturb the material integrity. *The issue of operation safety of hot dip galvanized steel structures is one of the priorities to which a reliable answer is being looked for.* More detailed findings about the course of the stress state of a steel object exposed to uneven heating during gradual immersion into molten zinc and about changes caused during this process in steel are the basic prerequisite for thorough analysis of this issue in all physical and metallurgical contexts as well as for formulation of reliable conditions for safe use of hot dip galvanized steel structural elements. In the European standard *EN 1090-2 Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures* hot dip galvanizing is dealt with in Annex F. Besides principles for achieving the required characteristics of the coating and checking its quality Chapter F.7.4 sets forth that from the point of view of occurrence of cracks the part specifications must contain information about a possible risk of this defect and requirements for the follow-up check after the galvanizing.

2. Contributing factors during hot dip galvanizing

The best-known factors and phenomena that accompany the occurrence of cracks during hot dip galvanizing mentioned in literature include:

- Hydrogen embrittlement
- Shaping
- Unsuitable design and welds
- Liquid metal assisted cracking

However, the occurrence of cracks is influenced by the thermal characteristics of the hot dip galvanizing process to the highest extent [5]. These characteristics are discussed in a separate chapter of this paper.

Fig. 1. Hot dip galvanizing of prefabricated load-bearing steel components

Fig. 2. Tempering brittleness

2.1. Hydrogen embrittlement and tempering embrittlement

During pickling in hydrochloric acid nascent hydrogen is released, which moves into places with a lower value of its partial pressure, into steel in the particular case. Atomic hydrogen interstitially travels in the crystal lattice of iron and after the end of pickling it either escapes from the steel into the atmosphere or gets stuck in places where it can recombine (“hydrogen traps”). There it causes gas pressure in the order of several hundreds of MPa, impairing the material characteristics [7]. During hot dip galvanizing of welded pieces tempering brittleness may develop under certain conditions (Fig. 2). It is related to precipitation of carbon at the border of austenitic grains [7]. It is true that structural steel has a ferritic structure in the natural state; however, in welds or areas influenced by heat the presence of residual austenite cannot be ruled out.

2.2. Bent elements

Bending at elevated temperatures is especially dangerous as the material unlike the cold state loses some toughness and the risk of formation of numerous macro-cracks rises. Plastic deformation in steel causes considerable disturbance of the crystalline structure, the cohesion at the grain borders decreases. Especially at the drawn side the material characteristics get worse and steel becomes very brittle. Contact with molten metal may cause spontaneous integrity failures (Fig. 3).

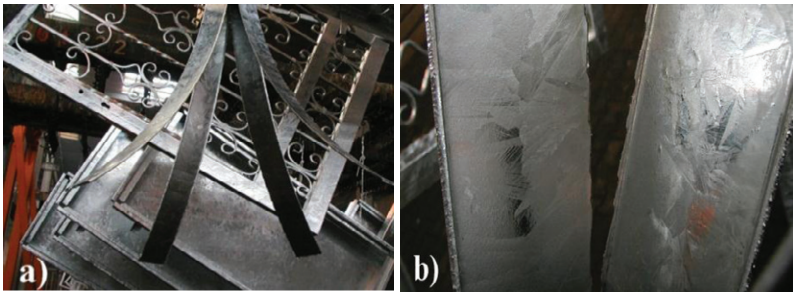

Fig. 3. Steel becoming brittle due to bending – (a) view, (b) detail

Fig. 4. Unsuitable welds

2.3. Unsuitable design and welds

Parts intended to be hot dip galvanized must be designed in such a way that they can be quickly immersed in the molten zinc and at the same time individual structural elements must be allowed to freely expand in case of uneven heating. In welds a jump change of material characteristics occurs. Every weld, regardless of the quality of its execution, is a notch where stress can concentrate. Rigid, unyielding structures as lattice girder, thick-walled frames with a box design, etc. represent a risk for the occurrence of cracks (Fig. 4).

2.4. Liquid metal assisted cracking (LMAC)

The LMAC hypothesis is based on the assumption that liquid metal atoms easily penetrate along the borders of the substrate grains, reducing its cohesion there [4]. In combination with tensile stress the integrity of the substrate in the surface layer may be impaired, which results is quick growth of cracks formed this way (Fig. 5). The LMAC theory is supported by analyses of cracks of affected hot dip galvanized parts [3]. Inside brazed fractures an increased content of metals with a low melting point which zinc baths are alloyed with (Sn) was found [2]. Experiments have shown that the LMAC phenomenon is manifested on mutual combination of more unfavourable factors [1], [2], [8] as:

- tensile stress, namely stationary residual as well as variable caused by uneven heating in molten zinc;
- unsuitable design, especially presence of dangerous notches and a rigid, unyielding structure;
- improper execution of the structure (not thoroughly welded joints, bending at elevated temperatures,…),
- using steel with a high yield point;
- using steel that is prone to aging; ,
- increased content of risk metals in the zinc bath (tin, bismuth, lead);
- long-term effect of liquid metal on the surface of galvanized parts;
- unsuitable position of the parts on the suspension during galvanizing;
- low speed of immersion in the zinc bath.

Another theory inclines to the principle of crack propagation supported by liquid metal (Fig. 6). It is based on the assumption that the crack opening rate and the speed of formation of the alloy phases are in mutual harmony so that the liquid metal can proceed towards the front of the crack where it starts to react with the substrate, producing more voluminous alloy phases that put pressure on the crack walls, supporting its propagation.

Fig. 5. Cracks on a truss after hot dip galvanizing

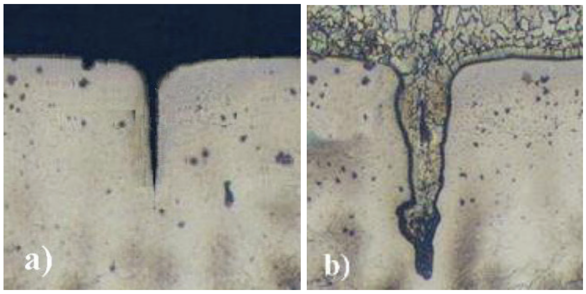

Fig. 6. Crack propagation - (a) before, (b) after galvanizing (photomontage)

3. Thermal characteristics of hot dip galvanizing

The fact that during hot dip galvanizing steel parts are exposed to extreme force effects was still underestimated in the recent past [5]. The cause of the occurrence of cracks was ascribed to hydrogen embrittlement and deformations of components were explained by the release of the residual tension.

3.1. Gradual heating up of the material from the surface to the core

A steel object abruptly immersed in molten metal is heated up gradually from the surface to the core. Due to heat expansion the volume of the material in the heated up surface layer expands and gets stuffed in the radial direction. At the same time the enhanced temperature significantly reduces its yield point, ductility and other material characteristics. During gradual heating up of the object the core expands with a certain delay, causing double-axis tension in the stuffed surface layer. Single-axis relative deformation achieves the value of 0.516 at the temperature difference of 430°C. This value of relative deformation is too low to cause cracks, but the tension in the surface layer reaches the yield point of structural steel (in an extreme case up to 1083.6 MPa).

3.2. Bimetallic effect

An increased risk of crack formation during hot dip galvanizing of parts made of steel with a higher yield point is documented by an analysis of thermal effects on an object during its gradual immersion in molten zinc [5]. The part of the object that is immersed is quickly heated up while the part above the bath surface is relatively cold. Bimetallic co-action of two mutually coupled elements of the same material, but at different temperatures occurs. Stress in the steel caused by its heat expansion generally reaches the yield point of the material, the deformation occurs in the range of plasticity and the hot dip galvanized objects get deformed. Structural steel of the usual quality is characterized by a low value of the yield point. Plastic deformations of this steel type are caused at relatively low tension and the material relaxes. A part made of lower-quality steel is thus exposed to lower force effects than high-quality fine-grained structural steel with a high yield point. *Force effects caused by uneven heating are directly proportional to the immediate yield point of the material.* Structural parts of high-quality steel with a higher yield point value are exposed to a higher load during hot dip galvanizing; therefore they face a higher risk of integrity failure in places with a high concentration of tension [6].

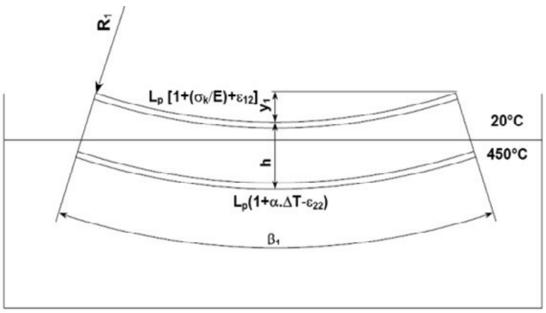

Fig. 7 Deformation of a beam exposed to uneven heating

Fig. 7 indicates a trivial situation when the bottom flange of a beam of length L_p is heated up to the bath temperature while the cold top flange has the ambient temperature (the influence of the post is neglected). If the tensile stress in the cold top flange reaches the yield point σ_k, then considering the heat expansion coefficient of steel α, temperature difference between the top and bottom flange of the beam ΔT, elasticity modulus of steel E, relative plastic extension of the cold top flange ε_{12} and relative permanent contraction (stuffing) of the heated bottom flange ε_{22}, the resulting geometry of the segment [5] can be determined with an acceptable degree of uncertainty and the state of stress can be assessed. However, suggesting a true mathematic model to describe time dependent variable effects of hot dip galvanizing on a real part galvanized under real conditions is very difficult. There are a number of concurrent variable influences and limiting conditions as coefficients of heat expansion, heat conductivity, heat transfer as well as specific heat and specific material weight of the galvanized part, the speed of immersion of the galvanized part and the dwell time in the zinc bath, the entire geometry of the zinc part. geometry of passage of the galvanized part through the bath surface, instantaneous value of the yield point of the material of the galvanized part and the moment it is achieved, influences of notches and the state of the surface of the galvanized part, mutual force effects between individual structural elements of the galvanized part, chemical composition and temperature of the zinc bath, pre-heating temperature of the galvanized part, flow of the molten metal around the surface of the galvanized part, etc. For example, prof. Markus Feldmann made such an attempt in his [1] formulation of the immersion condition (1). It is based on the Newton cooling law for determination of local density of heat flow, when the corresponding heat differential is expressed as energy necessary to heat up a plate object by the temperature differential. The condition (1) is the result of integration in the interval between the temperature of the pre-heated part and the melting point of zinc.

$$\frac{t_\sigma}{t_{\alpha t}} = k_c \cdot \frac{h.2\alpha_t}{C \cdot s \cdot \rho \cdot v} \cdot \frac{1}{\ln \dfrac{T_{Bath} - T_V}{T_{Bath} - 419}} \leq \eta \qquad (1)$$

t_σ	[s]	dipping time (time for passing of the cross-section of the structural component through the bath surface)
$t_{\alpha t}$	[s]	heating time for attain the melting temperature of zinc (419°C)
h	[m]	height cross-section of the structural component
α_t	[W.m^{-2}.K^{-1}]	effective value of heat transfer coefficient of the zinc melt
C	[J.kg^{-1}.K^{-1}]	specific thermal capacity of steel
s	[m]	plate thickness
ρ	[kg.m^{-3}]	density of steel
v	[m.s^{-1}]	dipping speed
T_{Bath}	[°C]	temperature of the zinc melt
T_V	[°C]	preheating temperature of a structural component
k_c	[ ]	adjustment factor depending on structural detailing
η	[ ]	immersion factor

The condition (1) expresses the fact that at a certain time $t_{\alpha t}$ necessary to heat up the part the time t_{σ} required for the passage of the part cross-section through the bath surface should be as short as possible. It is desirable that the value of the $t_{\sigma}/t_{\alpha t}$ fraction should be low. However, the possibility of pre-heating the galvanized part contradicts the condition formulated this way (1). A higher pre-heating temperature logically means a lower risk, but it also means a reduction of the time necessary to heat up the part ($t_{\alpha t}$) and consequently it leads to an undesirable increase of the value of the $t_{\sigma}/t_{\alpha t}$ fraction. Introduction of the coefficient k_C to compensate this disproportion represents denial of validity of the derived relationship.

4. Execution of hot dip galvanized steel structures

In 2009, the final report of the *Hot-dip-zinc-coating of prefabricated structural steel components* task [1] was issued, which was solved under the auspices of the Joint Research Centre of the Commission. The aim of this task was to provide a report on the state of knowledge of the LMAC phenomenon and to derive rules to avoid execution of a steel structure made of supporting parts affected by cracks formed during hot dip galvanizing. The content of the above mentioned report corresponds to the content of a greater part of the guideline *DASt-Richtlinie 022 – Guideline for hot-dip-zinc-coating of prefabricated load-bearing steel components* [9] issued in Germany at the end of the same year. The material content of the *DASt-Richtlinie 022* guideline should have been incorporated in the new European standard after its short verification. However, this has not happened yet as the issued guideline invoked a discussion since on the one hand it represents a certain discrimination tool against the other member states of the European Community as regards marketing of their products in Germany and on the other hand some scientific conclusion adopted here appear to be unfounded. However, in principle, one must conclude that the *DASt-Richtlinie 022* guideline represents an integrated and in its greater part an applicable tool for prevention of cases of failure of hot dip galvanized structures. *Section 4* summarizes and presents instructions in the form of synoptic algorithm based on widespread empirical experience with hot dip galvanizing of steel structural parts. Observing the procedure in accordance with *Section 4* for new constructions means a guarantee that supporting steel structures will not be made of parts that might be affected by cracks caused by the LMAC phenomenon. As regards the annexes of the *DASt-Richtlinie 022* guideline it is especially *Annex no. 3* that is worth mentioning as it deals with the execution of non-destructive tests for the presence of cracks using the magnetic powder method (MT tests).

5. Conclusion

The absence of a binding European regulation that would efficiently deal with the issue of reliability of important steel structures made of hot dip galvanized supporting construction elements is gradually becoming pressing for the European standardization and appears to represent a deepening shortcoming that undoubtedly deserves greater attention.

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