Galvanizing Structural Steelwork

BCSA

BCSA and GA Publication No. 40/05

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An Approach to the Management of Liquid Metal Assisted Cracking

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Publication Number 40/05
First Edition 2005
ISBN 0850730481

British Library Cataloguing-in-publication Data
A catalogue record for this book is available from the British Library

THE BRITISH CONSTRUCTIONAL STEELWORK ASSOCIATION LTD

BCSA is the national organisation for the steel construction industry: its Member companies undertake design, fabrication and erection of steelwork for all forms of construction in buildings and civil engineering. Associate Members are those principal companies involved in the purchase, design or supply of components, materials and services etc., related to the industry. Corporate Members are clients, professional offices, educational establishments, etc which support the development of national specifications, quality, fabrication and erection techniques, overall industry efficiency and good practice.

The principal objectives of the Association are to promote the use of structural steelwork: to assist specifiers and clients: to ensure that the capabilities and activities of the industry are widely understood and to provide members with professional services in technical, commercial, contractual and quality assurance matters.

The Association's aim is to influence the trading environment in which member companies have to operate, in order to improve their profitability.

A current list of members and a list of current publications and further membership details can be obtained from:-

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GALVANIZERS ASSOCIATION

Galvanizers Association is the representative body for the hot dip galvanizing industry in the UK and Ireland with a membership of 71 of a total of 85 plants. Its member companies process 93% of all steel galvanized in the UK and Ireland.

The industry itself has been in existence for more than 150 years. It has endured against newer technologies because it still provides a very cost effective and environmentally sustainable means of protecting steel against corrosion.

The Association was set up in 1949 to encourage the highest possible standards of technical efficiency in the industry and to promote the use of hot dip galvanized steel.

GA operates with a permanent staff of eight providing a breadth of technical, health & safety, environmental and marketing support and information. It also acts as an industry advocate, ensuring that the consensus views and interests of member companies are fairly and consistently represented in national and international regulatory discussion.

The Association is an authoritative source of information on all aspects of galvanizing. It produces publications; many of them free and has staff available to discuss relevant problems and answer technical enquires from specifiers, users and its member companies.

GA maintains a high level of awareness of technical and environmental developments relevant to the industry and ensures these are communicated effectively.

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Foreword

Liquid Metal Assisted Cracking is a form of cracking that may occur when steel components come in to contact with molten zinc. This form of cracking is uncommon but if it is not detected and repaired it can have extremely serious consequences on the performance of the structure.

A Working Group was set up in 2002, comprising members of the Galvanizers Association (GA), members of the British Constructional Steelwork Association (BCSA), Ove Arup and experts to explore the issues surrounding Liquid Metal Assisted Cracking (LMAC), to prepare guidance on the mechanism and how it may be avoided. Interim guidance was published (in May 2003) in a document titled "Guidance Note: The design, specification and fabrication of structural steelwork that is to be galvanized" (available from both GA and BCSA).

The Working Group has continued its work, and this document "Galvanizing Structural Steelwork – An Approach to the Management of Liquid Metal Assisted Cracking" is the culmination of that work. The guidance given in this publication assists in the development of designs and details with low susceptibility to LMAC and an appreciation of the relative importance of the factors adding to that risk from practical experience of cracking.

In the UK, few cases of LMAC have been reported, and fewer still investigated thoroughly (with metallurgical analysis) and much of the evidence tends to be anecdotal. The Galvanizers Association and the British Constructional Steelwork Association would welcome any information stemming from projects where cracking during galvanizing has occurred, so that the knowledge-base can be built upon.

[1] The Employer's, or the Steelwork Contractor's, designer who is responsible for the structural design and for reviewing and accepting the detail drawings and erection method statement

Contents

1. Introduction

The galvanizing of structural steelwork is a long established and cost-effective way of providing economic and long-lasting protection against corrosion, with low maintenance requirements and good damage resistance.

The UK galvanizing industry galvanizes some 800,000 tonnes of steel annually, an increase of a third over the past decade. Larger zinc baths have been introduced in response to the construction industry's needs to hot dip galvanize longer and larger components. The UK boasts the longest bath in Europe (at 21 metres) and there are another twelve baths in the UK and Ireland in excess of 10 metres long.

In recent years the phenomenon known as Liquid Metal Assisted Cracking (LMAC) has been recognised as a form of cracking that may under some circumstances occur, for example during the galvanizing of structural steelwork. Although this form of cracking is uncommon, if it is not detected and repaired it could have extremely serious consequences on the performance of the structure.

The occurrence of LMAC depends on a range of factors coming together at the same time. These factors derive from the design and detailing of the component, the condition and quality of the steel, fabrication and the galvanizing process. The weighting of the individual contributions from each of these activities is not known and no single factor, at this time, can be identified as the major contribution to LMAC.

This publication gives advice to clients, specifiers and engineers on LMAC, describes the factors that may contribute to the risk of LMAC occurring, and recommends a regime of post-galvanizing inspection that should be undertaken. It should be noted that the current British Standard BS EN ISO 1461: 1999 'Hot dip galvanized coatings on fabricated iron and steel articles – Specifications and test methods [30] does not address the issue of LMAC.

The advice given is applicable, primarily, to galvanized structural steelwork for building construction in the UK. It is based on steel grades S275 and S355, although the principles, if used with care, can be applied to the management of higher strength grades of steel.

The methodology may also be modified for bridge structures or series-production of steel 'components'. However, if the structure is to be subjected to fatigue loading the consequences of structural defects are far more critical and the Engineer must consider the inspection regime in the light of these consequences.

Traditional UK practice for building steelwork is for the connections to be designed by the Steelwork Contractor to forces provided by the Engineer[1]. Therefore some of the measures to control LMAC will be the responsibility of the Engineer and others will be the responsibility of the Steelwork Contractor. As in most matters, cooperation between the two parties is essential to provide the best solution.

The vast majority of steelwork that is galvanized has little susceptibility to LMAC, but the guidance contained within this document helps to identify the circumstances where any increased risk for building construction can be ameliorated through improved:

1. Design and detailing
2. Type and quality of steel
3. Fabrication
4. The galvanizing process

The guidance and the post-galvanized inspection presented in this publication, represent a pragmatic approach to reducing the potentially serious consequences of LMAC should it occur and not be detected.

By following the guidance and the advice set out in this publication and by committing a modest amount of attention to detail at each stage of the construction process, the chances of LMAC occurring can probably be substantially reduced.

[1] The Employer's, or the Steelwork Contractor's, designer who is responsible for the structural design and for reviewing and accepting the detail drawings and erection method statement

2. The Galvanizing Process

All common steels can be hot dip galvanized, but the speed of reaction in the bath and the resulting zinc/alloy coating thickness is dependent upon the chemical composition of the parent metal (and, in particular, its silicon content) and the chemistry of the contents of the galvanizing bath [1].

The steel component is first chemically cleaned and then dipped into the molten zinc, which is at a temperature of about 450ºC. Layers of steel/zinc alloy are formed, providing a transition from the 'inner' steel substrate to a surface of zinc overlying the alloy layers. The outer zinc layer, combining with the external atmospheric conditions, provides a slowly-weathering coating, with comparatively hard alloy layers providing further damage and abrasion resistance properties. The average 'weathering loss' is approximately 1.5µm/year, giving a life in excess of 50 years for the average coating thickness of 85µm (See the Zinc Millennium Map for further details [2]).

It is important to note that the process of galvanizing steel can be described as 'aggressive'; at 450ºC the yield strength of steel is approximately 50% of its strength at normal ambient temperatures, but its strength is regained as the steel cools after galvanizing [3].

Issues of design, good detailing, sound workmanship and 'locked in' stresses assume much greater significance when hot dip galvanizing is specified, as is indicated later in this document. Advice on 'normal detailing' for galvanizing (for example, vent holes) is available from the Galvanizers Association [4].

Careful consideration must be given to these issues by the Engineer, specifier, material supplier, Steelwork Contractor and galvanizer. Normal good fabrication practice, such as adherence to the workmanship requirements of the National Structural Steelwork Specification (NSSS) [5], should be the minimum standard of fabrication.

This guidance note is based on the assumption that good practice has been followed at all stages of the fabrication and galvanizing of steelwork components.

The process of galvanizing steel can be a catalyst for cracking to occur. Three cracking mechanisms are well-known, researched, understood and easily avoided, whilst the fourth is less well-known. These are:

1) **Distortion Cracking** – where very high residual stresses (arising from rolling, cold forming, welding, thermal gradients etc) cause cracking to occur

2) **Hydrogen Embrittlement** – where atomic hydrogen (introduced during steel manufacture, the welding/fabrication processes or the chemical cleaning prior to galvanizing) diffuses to, and accumulates in, regions of dislocation in the microstructure of the steel.

3) **Strain Age Embrittlement** – arising from extensive cold working of the steel followed by ageing or warm-working the steel at a temperature less than 600ºC. This form of cracking is not usually significant in structural steelwork.

4) **Liquid Metal Assisted Cracking**

Considerable guidance on the first three modes of cracking and their avoidance through normal caution and good practice is readily available from the Galvanizers Association, and these forms of cracking are normally avoidable.

The fourth cracking mechanism, LMAC, is uncommon but its consequences, if it is not discovered and repaired, may be extremely serious – as would be any form of cracking left unaddressed. This fourth type of cracking is the subject of this publication.

3. Liquid Metal Assisted Cracking (LMAC)

The phenomenon of liquid metal assisted cracking (or liquid metal embrittlement as it is known in the USA) has been known for several decades, but its occurrence is sufficiently uncommon that no coordinated programme of research or information gathering has been put in place in the UK. However, some research is ongoing at present in the UK involving Corus and other European steelmakers [6]. Even where cracking has occurred and has been diagnosed as LMAC, it is likely that only a limited number of components will have cracked, but for the components that have cracked the size of the crack will vary and some will not be visible due to the combination of crack size and a coating of zinc.

Whilst evidence from Germany [7], Japan [8], the USA [9] and other countries [10,11,12,13,14,15] has highlighted the occurrence of LMAC, an authoritative understanding of the circumstances that may trigger the cracking remains elusive.

It is, however, recognised that a range of factors can and do influence the onset of LMAC, and that the inter-relationship of these factors is also of crucial importance to any understanding of the phenomenon. The relative weighting of these factors has yet to be defined but clearly, all the partners in the supply chain for galvanized articles have some part to play in influencing the level of risk associated with LMAC.

Liquid Metal Assisted Cracking (LMAC) is a phenomenon that may occur when steel components are hot dip galvanized, but it is important to note that this form of cracking can only happen when the steel is in contact with molten zinc.

Figure 1. An example of LMAC

LMAC may be characterised by a crack through the entire cross-section that is clearly evident when the component is lifted from the bath (an example of LMAC is shown in figure 1 and more examples are shown in Annex C), but it is also possible that the crack will not have travelled through the whole cross-section, will have filled with zinc, (and other metals within the galvanizing bath) and the zinc will also have been uniformly deposited over the surface of the steel, rendering the crack invisible to visual inspection. Nevertheless the recommendation of this report is that all structural steelwork to be galvanized should be subject to 100% visual inspection. Generally cracks are initiated at fabrication details such as welds, gas-cut edges, holes etc and therefore a visual inspection should be initially concentrated around these areas. Additional inspection, if required, should be limited to those areas discussed in Section 4.

Normal fabrication practice is that the fabricated steelwork is inspected for defects before it leaves the Steelwork Contractor's workshop. The detection and remediation of unacceptable defects [i.e. outside the specification for supply quality] is very important at this stage whether the steelwork is being sent for galvanizing or the application of any other form of corrosion protection. Careful visual inspection of the fabricated component is required to ensure unacceptable defects are not present prior to application of any corrosion protection system. Once cleared it is transported to the galvanizer's workshop and then direct to site for erection. Visual inspection after galvanizing has historically focused only on the adequacy of galvanizing and the quality of finish of the product. It is now recommended that 100% visual inspection is carried out after galvanizing to specifically examine the steel components for LMAC defects. This inspection can take place at the galvanizer's works or any point up to the erection stage of the project. Additional inspection using other NDT techniques may also be appropriate under some circumstances and this is discussed in Section 4.

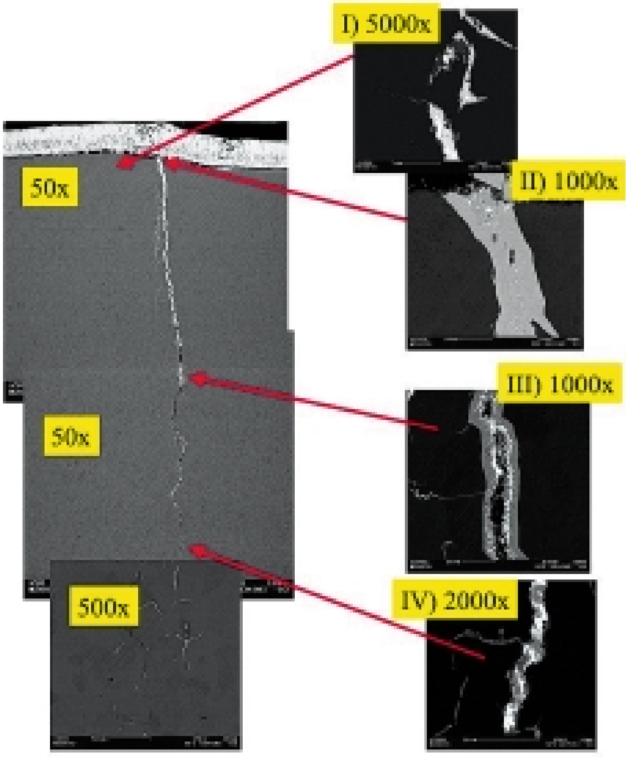
3.1 Metallurgical Aspects

Certain solid metals when in contact with other liquid materials can give rise to a reaction, which will affect the parent solid metal. Susceptibility to these conditions occurs only in specific metals and environments, and is known under the generic title of liquid metal embrittlement. One of the situations where this can occur is when structural steel is stressed and in contact with liquid zinc as happens during the galvanizing process, i.e. LMAC.

LMAC is the sudden and rapid brittle failure of a normally ductile material when coated or in full contact with a liquid metal and stressed in tension. The fracture mode changes from ductile to a brittle intergranular or a brittle transgranular (cleavage) mode. In most test cases it is reported that the initiation and propagation of the cracks appear to occur simultaneously and propagate through the entire specimen at speeds of between 10 and 100 cm/second [8].

Examination of the fracture surfaces shows complete coverage by the liquid metal. A report by M. H. Kamdar [9] states 'The distinctive features of embrittlement and of the resultant fracture surfaces are a significant loss in mechanical properties and usually a brittle fracture mode. The fracture surfaces and their appearances are easily distinguished from those due to stress corrosion cracking (SCC) which is similar to fracture due to hydrogen or temper embrittlement.' Brittle fracture surfaces that exhibit fast or total fracture, significant loss in ductility and strength, and the presence of solid metal at the tip of the propagating crack that has resulted from liquid metal flowing to the tip of the crack are some of the characteristics which may be used to distinguish LMAC from other environmentally induced failures. A micrograph showing a typical LMAC crack is shown in figure 2. For further reading on the metallurgical aspects of LMAC the reader is referred to the report by M. H. Kamdar [9] and the American Institute of Steel Construction report on 'Current knowledge of the Cracking of Steels During Galvanizing' [31].

Figure 2. Micrograph of a typical LMAC crack (Courtesy Langenberg, P. 'REM-EDX-Analyse eines Verzinkungsrisses im Bereich der kaltumformung durch den Boxer', IWT Bericht, 18.11.2003 unpublished)



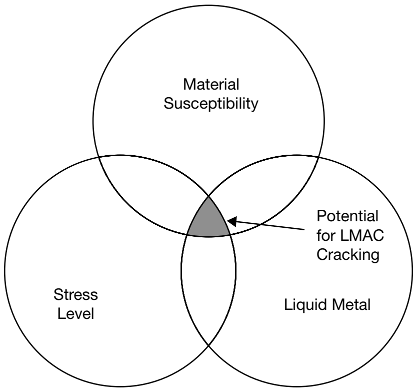
It is important to appreciate that once the material has been galvanized and removed from the bath it will return to its full strength and there will not be any deleterious effects upon any of the mechanical or metallurgical properties of the steel. However, if a crack has formed in the steel section during the galvanising process this will create a stress concentration. An undetected crack of sufficient size has the potential to result in immediate unstable fracture or plastic collapse. For structures subject to fluctuating loads small cracks may provide initiation sites for fatigue cracks, which can eventually result in premature failure.

3.2 Prerequisites for LMAC

It is generally accepted that there are three main prerequisites for LMAC to occur. These are:

- stress level (i.e. where the local stress is greater than the yield stress)
- material susceptibility
- liquid metal

Figure 3. Diagram showing the interaction of stress level, material susceptibility and liquid metal



Stress Level	Material Susceptibility	Liquid Metal
Internal material stress	Steel chemical composition	Impurities
Cold deformation/ Prior strain	Yield strength Carbon equivalent value	Temperature Intentional additives
Welding residual stress	Residual stresses Hot rolling process	
Restraint Fabrication process	Hardness	
Thermal stress: immersion rate variable thickness differential temperature		

Practical Factors

- Thickness ratio
- Welds: fillet/butt
- Depth of member (stiffness)
- Holes: drilled/punched
- Member profile
- Type of section/component
- Type of truss
- Pre-heat
- The presence of a notch, shelling or other steel defects

Table 1. Prerequisites for LMAC subdivided into their constituent parts

The basic premise is that, where all three 'prerequisites' exist together, there is a risk that LMAC might occur. This is shown diagrammatically in figure 3. It is also self-evident that all three are present when fabricated structural steelwork is hot dip galvanized.

It is perhaps more important to recognise the individual and independent factors comprised within the three prerequisites given above. The lack of knowledge surrounding LMAC has to do with the inter-relationship of these individual factors, and their relative 'weighting' in increasing the risk of LMAC. Table 1 shows the breakdown of these three prerequisites into their constituent factors

Although the basis of the mechanism is recognised, the details of how material susceptibility and liquid metal (severity) factors may vary and affect the 'risk' are not known. Similarly, the effect of 'stress' has not been quantified.

4. Inspection

The Engineer should specify 100% visual inspection after galvanizing for all structural steelwork in building construction (Inspection reference PGI-1). Where there is a particularly critical or susceptible detail or when the consequences of structural failure of a single member is sufficiently high, the Engineer should consider whether the risk of LMAC is such as to warrant any post-galvanizing inspection in addition to the visual inspection (inspection reference PGI-2). Any additional inspection required by the Engineer (PGI-2) must form part of the Project Specification.

By following the guidance in Section 6 the possibility of Liquid Metal Assisted Cracking should be minimised. To further minimise any problems the Steelwork Contractor must ensure that any agreed post galvanizing inspection is completed, although it may be delegated to a subcontractor, the galvanizer or some other competent agency. The inspection regime on the post-galvanized structure should be as detailed in the Project Specification.The inspection regime should be set out in the quality plan which is approved by the Engineer prior to fabrication. In the event that additional testing is required by the Engineer suitable instruction should be given.

As a minimum a 100% visual inspection is recommended. This may be followed by a more detailed inspection using non-destructive testing if cracks are identified during the visual inspection. The recommended inspection regime, which should take place as soon as possible after galvanizing, is shown in table 2. In the event that a crack is found the job should be stopped and the design, fabrication and galvanizing process re-evaluated. The steel used should also be checked for compliance against specifications and that welding procedures used are appropriate for the CEV for those materials showing defects.

The areas to be visually inspected should be defined by the Engineer taking in to account the type of structure and the criticality of the members. Particular attention should be paid to inspecting likely crack initiation sites such as welds, corners, gas-cut edges, holes etc.

Annex C gives a pictorial library of LMAC cracks which can be used to help identify the type of crack and possible crack initiation sites in a visual inspection.

Consideration should be given in the quality plan, to critical or sensitive areas of the fabrication that might be subject to higher levels of post-galvanizing inspection in the event that defects are found. This should be specified by the Engineer in the Project Specification.

Visual inspection is very effective for significant cracking but for smaller cracks that cannot be detected by visual inspection, NDT systems are required. If LMAC cracking is present in a structure, then it can normally be expected that some of the cracks may be large enough for identification through visual inspection. The use of additional NDT would not normally be considered unless there is evidence of a susceptibility to cracking and then it should be targeted at the areas where cracks have been identified. Available NDT systems include Eddy Current Inspection (ECI), Magnetic Particle Inspection (MPI) and Ultrasonic Testing (UT). None of these were developed for hot dip galvanized structures and some of these systems can suffer some loss in sensitivity in the presence of a galvanized coating. Table 3 describes the impact of galvanizing on the sensitivity of different NDT systems.

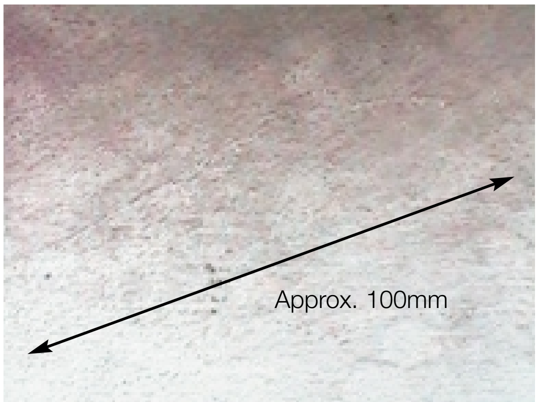


Figure 4a. Stiffener before MPI

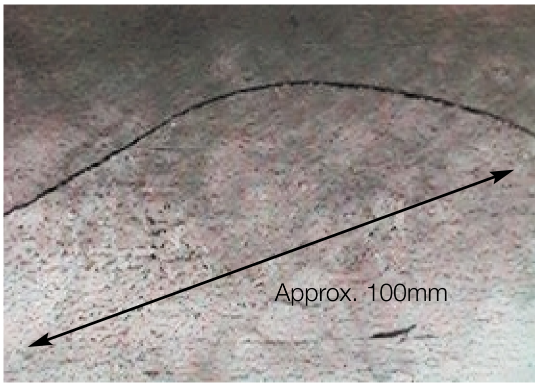


Figure 4b Stiffener after MPI

Post Galvanizing Inspection Reference	Level of Inspection
PGI-1	100% visual inspection of components and joints. The inspector should be suitably qualified (as defined in clause 5.5.3(ii) of the National Structural Steelwork Specification [5]), and should be familiar with the fabrication details and possible crack initiation sites. Inspection records should be produced and made available to the Engineer when requested. Any further defects or indications shall be reported immediately and further inspection (NDT) used to verify the report. If cracking is confirmed then an inspection schedule shall be developed for all steelwork to ensure that other members are free of cracks.
PGI-2	Non-destructive testing (NDT) generally on areas where defects have been found through visual inspection or other areas identified by the Engineer either in the Project Specification or noted on drawings.

Table 2. Post Galvanizing Inspection

NDT Technique	Effect of Galvanizing
Magnetic Particle Inspection (MPI)	Sensitivity is reduced by any coating which separates the ink from the cracked steel surface. A typical galvanizing coating thickness (70mm-100mm minimum specified) is well above the maximum recommended limits for reliable MPI (50 µm). MPI does work for most cracks below galvanizing but gives a 'fuzzy' crack line (see Fig. 4a). To be effective the operator must be trained to recognise the diffused indicators due to the presence of the zinc coating.
Eddy Current (ECI)	Good for inspection through coatings, but sensitivity is compromised by changes in section thickness and proximity to edges. EC will work for most cracks below galvanizing but requires more skill to obtain accurate results, with special training and equipment that most Steelwork Contractors will not be familiar with.
Ultrasonic Testing (UT)	Unknown effects of galvanized coating on coupling and reflectivity of a crack filled with galvanizing. UT is not suitable for inspection of many details. UT is not recommended for LMAC.

Table 3. Capabilities of non-destructive testing techniques for the detection of LMAC

Recognising the limitations given in Table 3, the most appropriate technique, at this time, is MPI providing that the operator is trained to recognise the diffused indicators due to the presence of the coating. Figures 4a and b show images before and after MPI for a stiffener.

5. Repair

Most cracks in a galvanized component can be repaired using an appropriate welding repair procedure. An example of a welding procedure is shown in Annex A. The Engineer should request that the Steelwork Contractor prepare a welding procedure for approval and the Steelwork Contractor should then carry out the repair. During the repair the procedure should ensure that the crack is completely removed and MPI should be used to ensure that this is the case.

Prior to repairing the crack all galvanizing must be removed from the area to be welded. This is essential as the fumes from the zinc can give rise to health and safety problems[2]. Galvanizing should be removed from the crack by grinding, gouging etc as molten zinc caused by weld heat can lead to further cracking from liquid metal penetration. It is therefore recommended that the galvanized coating in the vicinity of the weld repair should be removed by grinding back to bright metal to a distance of not less than 50mm from all edges of the repair. Almost all LMAC cracks penetrate through to the underside of the metal and therefore the galvanizing should also be removed from the opposite face.

It should also be noted that regions of galvanizing which have been heated above approximately 350°C during the welding process (e.g. the reverse side of a partial penetration repair) may also be damaged. To limit such damage, heat inputs and interpass temperatures should be maintained as low as possible, commensurate with other restrictions, such as the control of hydrogen cracking.

Once the crack has been repaired it is necessary to repair the protective treatment system on the component. Zinc rich paints are generally the simplest to apply in a site situation, but several coats may be required to match the long-term corrosion protection of the original galvanized coating. The dry film thickness (DTF) of the repaired member should be at least 30µm more than the original coating thickness requirement [see Table 4 below].

Zinc metal spray can also be used but requires good surface preparation and such coatings need to be thicker than a hot dipped coating – a sealed 100µm sprayed is broadly equivalent to 85µm hot dipped. This type of coating is not normally used due to Health and Safety issues.

Low melting point zinc-tin-lead alloy rods or powders, applied at about 300°C, are very effective, but their suitability may be limited by difficulty of application in restricted access areas, or the time taken to cover large areas. Therefore although rods can be used this method is rarely practical.

It should be remembered that although the galvanizing will have been removed locally, the remaining zinc elsewhere on the component will still provide cathodic protection to the steelwork, limiting the impact of corrosion on the repaired area.

Type of paint	Material thickness	Required Local coating thickness of zinc	Recommended paint thickness (DTF)
Zinc-paste (with min 96% Zinc in dry film)	<1.5mm	35 µm	65 µm
	1.5 to <3mm	45 µm	75 µm
	3 to <6mm	55 µm	85 µm
	from 6mm	70 µm	100 µm
Zinc-Spray (with min of between 90-91% Zinc)	Similar thicknesses can be achieved with paint sprays but because of the lower zinc content of these paints a correspondingly thicker wet coat is needed.		

Table 4 Relationship between the required thickness of the original galvanizing and the recommended paint thickness

[2] When galvanized steel is welded, fumes of zinc oxide are produced. If inhaled in sufficient quantity, the fumes can result in "metal fume fever" or "zinc chills." In severe cases, vomiting can occur. These flu-like symptoms are of short duration and typically pass within a 24-hour period. The galvanizing should therefore be removed prior to welding and adequate ventilation and air fed welding helmets should be used.

6. Practical Guidance

6.1 Structural Design and Detailing

The Engineer for the structure should consider various arrangements for the protective treatment of the structural steelwork. Galvanizing is certainly a very effective protective treatment and can also be cost effective for many forms of structure. However, the Engineer must also recognise that the use of galvanizing can lead to LMAC defects that can in some circumstances be structurally significant. This does not preclude the use of galvanizing, but some controls should be introduced to minimise the potential for such defects going un-noticed and therefore not being repaired before the structure is completed.

There are a number of general design aspects which are important in minimizing any potential for steel cracking problems. Where potential for steel cracking is significant and where the Engineer has a choice, consideration should be given to the following items.

The Engineer should specify the minimum grade of steel that will do the job. Higher grade steels are regularly galvanized but are more likely to exhibit LMAC due to design considerations, steel chemistry and rolling stresses (i.e. stresses induced during rolling to the finish shape or improve yield stress) and fabrication detailing. Engineers should consider limiting the Carbon Equivalent value to reduce the steels susceptibility to LMAC (see Section 6.2). The Engineer should exercise care in the design of member components, so that they do not require excessive stiffening at the connection nodes.

Unbalanced internal stress states and variation in local restraint (such as arise on half end-plate connections) should, if possible, be avoided in steel constructions to be hot dip galvanized and alternatives such as bolted connections or full depth end-plates should be used.

Substantial changes in material thickness at any point will induce large thermal stresses, when dipped into the galvanizing bath as the thinner material will heat up much faster than the thicker material. A rule of thumb is to keep the ratio of the thick-to-thin members less than 2.5 to 1[8].

Symmetrical cross-sections are more advantageous than asymmetrical ones as they help to balance out the inherent stresses.

To minimise welding stresses the Engineer should stipulate the minimum welding requirements (size, weld metal, heat input) and if possible arrange welding to be balanced. Fillet welds are better than butt welds for fitments such as brackets and secondary stiffening, and in some situations intermittent welding should be considered where appropriate. The use of intermittent welding is an excellent way to minimise welding stresses. It also avoids creating air pockets between members that can easily lead to a pressure build up [with trapped air/water/galvanizing pre-treatment fluids producing superheated air/steam at the galvanizing temperature].

Balanced welding patterns should be adopted, particularly for asymmetrical components. The welds should be as close as possible to the axis through the centre of gravity of the entire profile. If they are not, they should be as symmetrical as possible, at the same distance from the axis through the centre of gravity. Asymmetrical cross-sections constitute a greater risk of warping, especially if thicker welds are positioned on one side, at a greater distance from the axis through the centre of gravity.

In lattice-type and other complex fabrications, as few redundant members as possible should be adopted, as these will increase stresses and distortions throughout the component members when heated. However, the need to minimise redundancy should be balanced against an overall appraisal of robustness and then weighted carefully against the suitability of galvanizing for a complex component.

Components in which any internal static redundancy leads to high secondary stresses in the zinc bath should be avoided.

The Engineer should consider whether any 'special' treatment needs to be specified for exposed cut edges and notches (e.g. grinding or reaming) particularly where, for example, copes have been cut in to the 'k' areas of beams – the latter often exhibiting higher strength, lower toughness characteristics compared to the flange edges, due to the roll forming and straightening history of the steel product process route [16], and for holes drilling rather than punching. The method of manufacture of the steel can have significant effects on the mechanical properties of the steel elements in the structure. Any special measures considered as prudent should be clearly communicated to the Steelwork Contractor in the Project Specification.

Any venting and drainage holes/cuts to assist during galvanizing should be as large as possible, few in number and should not be cut in the heat affected zone of the welds.

The Engineer should follow the design guidance contained within BS EN ISO 14713: 1999 [17] and the Galvanizers Association publication 'Engineers and Architects Guide to Hot Dip Galvanizing' [4]. This will ensure that there is adequate provision for venting and drainage.

6.2 Type and Quality of Steel

The quality of the steel should comply with the appropriate standards given in Table 2.1. of the National Structural Steelwork Specification (NSSS) [5]. The types of sections suitable for galvanizing include rolled sections, structural hollow sections, plates and bars complying with the appropriate standard shown in Table 2.1. of the NSSS [5].

The following steels may be considered to have a higher risk of cracking:

- Quench and tempered steels (BS EN 10025) [18]
- High strength grades (>355N/mm2 yield) (BS EN 10025 [19])
- Cold formed hollow sections (EN 10219) [20]
- Weathering steels (BS EN 10025) [21].

Stainless steel attachments should be fixed after galvanizing [22]

Cold worked sections have high residual stresses and care must be taking when galvanizing these sections.

Carbon equivalent can be used to control the hardness (to a target of less than 270HV10) of steel and has been shown to have a strong link to the susceptibility of the steel to LMAC. There is also strong evidence from Japan [23] that the risk of LMAC can be significantly reduced by limiting the Carbon Equivalent value, CE,(Es) to 0.44% or less [8]. Materials with higher hardness values or higher Carbon Equivalent values can be galvanized, but the risk of LMAC is far greater.

The two approaches for controlling steel's chemical composition are shown below;

$$CE=C+\frac{Mn}{6}+\frac{Cr+Mo+V}{5}+\frac{Ni+Cu}{15} \qquad 5.1$$

$$Es=C+\frac{Si}{17}+\frac{Mn}{7.5}+\frac{Cu}{13}+\frac{Ni}{17}+\frac{Cr}{4.5}+\frac{Mo}{3}+\frac{V}{1.5}+\frac{Nb}{2}+\frac{Ti}{4.5}+420\,B \qquad 5.2$$

Expression 5.1 is the recognised International Institute for Welding (IIW) formula for carbon equivalent while expression 5.2 is the equivalent of sensitivity for cracking during hot dip galvanizing and has been taken from the Japanese Industrial Standard G 3129 – 1995 [24]. In both cases the steel should have a CE or Es value of 0.44% or less.

The IIW formula is commonly used in the UK for weldability and is the simplest to comply with. The maximum value of CE recommended by Japanese research is above that used by many UK Steelwork Contractors for ordering steel and normally above that supplied by stockholders. However it is advised that the maximum level is defined in the Project Specification and stated on ordering, along with any other steel options required.

There is also evidence from Japan [8] that the presence of certain alloying elements in the steel can increase the possibility of LMAC, particularly the presence of Boron, but also to a lesser extent Vanadium. In Japan, it is now possible to buy steel that has been designed for galvanizing and takes account of these alloying elements along with other factors such as stresses induced in the raw steel sections due to the production process.

Limiting the steel's Silicon content can be used to control the thickness and the brightness of the galvanized coating. However, there is no evidence that steel with limited silicon content is more or less likely to exhibit LMAC. At the time of enquiry and order the suitability and the relevant product quality requirements for hot-dipped zinc coating should be agreed (Option 5, EN 10025 [19]). This is principally the maximum silicon level.

Steel for galvanizing should have a known product chemical analysis. For steel purchased direct from the manufacturer this is achieved by invoking the options given in BS EN 10025 [19] for product analysis on the material certificate. If the steel is purchased with only the ladle analysis stated the maximum permitted deviations in the chemical analysis, as shown in the steel specification, should be used for purposes of calculating the Carbon equivalent value.

There is some evidence from Germany [32] that the toughness of the steel may have an influence on the development of cracks during galvanizing. This work shows that the development of cracks in S235 to S460 grade steels increase with decreasing toughness.

Work in the USA [31] indicates that there can be a significant variation in the mechanical properties exhibited by steel products depending on the location on the finished product, the specific manufacturing route used and the conditions experienced by the material. The most notable are variations in yield strength, tensile strength and toughness associated with the 'k' area (the meeting point between the web and the flange) compared to the mid-flange area on a hot rolled section. The 'k' area can show increased yield and tensile strengths with a marked reduction in toughness. This can have implications for both an increased potential for crack initiation and a reduced potential for crack arrest.

6.3 Fabrication

All of the following operations are a normal part of the fabrication process. It is assumed that good practice in fabrication detailing and methods, such as those set out in the National Structural Steelwork Specification [5], do reduce the LMAC risk, but do not prevent LMAC. However, depending on the type of steel component and construction in which it is to be incorporated, it may be necessary to adopt particular detailing and fabrication practices such as radius notches, grinding and finishing, for example to further reduce the risk of LMAC.

The Steelwork Contractor should ensure that the steel used conforms to the required specification and is not downgraded material from a higher specification, or steel from an unknown supplier. The steel should preferably be supplied by a source accredited to a national or internationally accepted standard (e.g. ISO 9001).

Stress is clearly an important factor and any steelwork fabrication will contain residual welding stresses approaching the parent metal's yield stress and residual stresses from rolling, cold deformation and heat straightening. In the hot dipping operation there are additional thermally induced stresses at levels dependent upon the 'overall local stiffness' of the component being dipped and the differential temperature and temperature gradients set up. Large changes in material thickness should be avoided, such as thin gussets on thick members, as this causes stress due to unequal heating rates.

It is clearly impossible to fully assess the level of stress during galvanizing as it will be a combination of all of these stresses. Since the risk of LMAC is directly related to the total stress levels in the steelwork after fabrication, combined with those generated in the galvanizing bath at elevated temperatures, it is these aspects that warrant major attention.

Steel members will be sheared, sawn or gas/plasma/laser cut to size and shape introducing further residual stresses. There may be a need for large holes or shapes to be cut and these again will add to the final stress pattern in the fabrication. Holes may be drilled or punched. Holes that are punched induce greater local stress than if the holes had been drilled. In South Africa [25] the most frequent encountered incidence of LMAC has been with cracks that have developed around holes that have been punched in relatively thick material. Where punching is used with 15mm or more thick material it is suggested that undersize holes are punched and reamed afterwards. Alternatively the holes can be drilled.

The Steelwork Contractor will then assemble the components and, in the case of complex assemblies, may have to force some members into precise alignment creating more stresses in some of the members. Following the guidance set out in the National Structural Steelwork Specification [5] is particularly important when the component is to be galvanized. The unit will then pass to the welders where further levels of residual stress will be induced in the steel component by the sequence of welding, the welding process and the welding procedures applied.

Welding operations are very important where steel fabrications are to be galvanized as normal metallurgical notches produced at every weld may assume significance as 'initiators' or stress raisers. Additionally welding can cause hydrogen embrittlement and adversely affect the steel's microstructure, particularly in the heat affected zone (HAZ). This can be avoided by following the recommendations given in the National Structural Steelwork Specification [5]. Control of the heat input may be required to prevent excessive hardness in the HAZ. The key issue here is to have a controlled heat input through operating to a suitable weld procedure. Cut edges including sheared and sawn edges should always be included in the visual inspection regime.

Defects on components such as, for example surface damage in the form of undercuts during welding (but also structural notches) should be in accordance with the National Structural Steelwork Specification [5].

As noted above, simply complying with the National Structural Steelwork Specification [5], EN288 [26] and EN1011 [27] will not remove the risk of LMAC but failure to comply with these standards may increase the risk of LMAC.

6.4 The Galvanizing Process

In addition to the factors identified above for structural design and detailing, the type and quality of the steel and the fabrication process, the galvanizing process is a factor contributing to the complex interactions which can result in LMAC. In the event that LMAC occurs or the risk of LMAC might occur is high, then it is recommended that the Engineer and the Steelwork Contractor should discuss the following issues with the galvanizer.

In common with the requirement for good practice at previous stages in the manufacture of a component [to minimise the presence of defects in the steelwork before the article is sent for galvanizing] the galvanizers should also seek to minimise the development of defects (e.g. hydrogen cracks) in the steelwork during the pre-treatment and galvanizing operations.

To minimize the risk associated with the development of hydrogen cracking during the cleaning stage, inhibited acid should be used to chemically clean the steelwork. The time the steelwork spends in the acid pickling bath (prior to galvanizing) should be the minimum necessary to allow chemical cleaning of the steelwork [29]. The required pickling time will vary significantly with the condition of the steel and the extent, depth and morphology of mill scale on the steel elements within the structure. Extended pickling times may result in excessive absorption of hydrogen, especially in susceptible areas such as the HAZ adjacent to the weld. Some dissipation of the hydrogen may also be expected.

Work in Germany [32] recommends pickling in not less than 8% free hydrochloric acid noting the added protection from hydrogen embrittlement derived from the use of inhibitors. The German work also recommends the use of high concentrations of flux – 400g/l to 500g/l – during pre-treatment work. These flux concentrations are very high and their use is not standard practice in the UK and Ireland.

Stripping the zinc off a component through pickling prior to re-galvanizing should be avoided whenever possible, but if it is necessary, then the re-galvanized component should be inspected with additional care as the risk of LMAC is likely to increase.

If a 'pre-heat' is available prior to dipping in the galvanizing bath (use of a hot flux and/or a drying oven for example), then its use may reduce the thermal stresses induced during galvanizing and may therefore lower the risk of LMAC.

To minimize the stresses induced through the galvanizing process, components should be correctly slung and adequately supported to minimise self-weight, thermal and bending stresses. Often this can be achieved by making the angle of dipping as steep as possible. Adequate drainage should also be provided to prevent an excess additional weight of zinc when removing the component from the galvanizing bath.

For most items single dipping is appropriate, but for very long or deep components dipping from one side and then the other is often necessary. This is called 'double dipping'. Depending on the structure of the component (e.g. large beam or trusses) double dipping may exacerbate thermal stresses or reduce them and trials may be appropriate in some circumstances to find the best method of support and dipping practice to minimise the potential for LMAC during this process.

The relative significance of melt-composition in the galvanizing bath on the potential for steel cracking has not been fully elucidated. Galvanizers will quite properly make up and maintain the galvanizing bath using a range of materials – primary zinc, secondary zinc, master-alloy additions and /or direct element additions to the bath. These latter chemicals are used to control the quality characteristics of the coated article – e.g. coating thickness, aesthetics and surface smoothness. In the UK and Ireland, galvanizing members of the GA operate to the requirements of the galvanizing standard BS EN ISO 1461:1999.

Interim guidance in Germany [32], reflecting the nature of their domestic steel, fabrication and galvanizing industries, indicates that it is beneficial to maintain a composition in the galvanizing bath that satisfies the following criteria:

$$\sum \text{(Tin (Sn) + Lead (Pb))} \leq 1.3\% \text{ (wt) and}$$

$$\text{Bismuth (Bi)} \leq 0.1\% \text{ (wt)}$$

It should be noted that this is not an absolute limit below which either LMAC can be guaranteed not to occur or above which LMAC will definitely occur on a more then rare basis. Historically, some regions external to the UK and Irish markets have operated galvanizing baths containing levels of Tin (Sn) much higher than those used domestically and so domestic galvanizers will not always reflect this experience.

The German work also advocates the use of high dipping speeds where possible and work from Japan [8] indicates dipping speeds approaching 5.5m/mim were found to be beneficial. Where preheats are utilized (see above) the time elapsed between preheat and dipping should be minimised. High dipping speeds will only normally be achievable when articles are well vented and the design allows for rapid access of the zinc and efflux of air. The dipping speed used should be commensurate with the design of the article without compromising worker safety or product quality.

The temperature of the galvanizing bath should be maintained at the lowest setting which allows for minimization of thermal stresses during dipping; minimization of overall dipping time and achievement of acceptable quality surface finish to the galvanized article, unless specific experience on a practical body of work suggests otherwise.

7. Concluding Remarks

Liquid Metal Assisted Cracking (LMAC) can occur when steel components come in to contact with molten zinc. This form of cracking is uncommon but if it is not detected and repaired it can have extremely serious consequences on the performance of the structure. It is generally agreed that there are three main prerequisites for LMAC to occur. These are:-

- Stress level
- Material susceptibility
- Liquid metal

Although the relative importance and the inter-relationship between these issues in increasing the risk of LMAC are largely unknown there is strong evidence to suggest that careful consideration of these issues with respect to the following activities can reduce the risk of LMAC:

- Design and detailing,
- Type and quality of steel
- Quality of fabrication
- The galvanizing process

This publication provides practical guidance to clients, specifiers and engineers on each of these topics to identify circumstances where any increased risk of LMAC can be ameliorated. Annex B of this publication gives a simple check list of the more important variables which affect critical decisions on the successful use of hot dip galvanizing. This check list can be used as a general guide.

A post-galvanized inspection regime is suggested as a pragmatic approach to reducing the potential consequences of LMAC on the structure. It is recommended that the Engineer of the structure should specify 100% visual inspection after galvanizing for all structural steelwork that is to be utilised in building construction. This should be written into the Project Specification so that all parties are fully aware of the requirement. In the event that some LMAC defects are found, then it is important that the Engineer should consider the potential implications of such cracking and modify the Project Specification as required to include further non-destructive testing in critical areas. The Engineer should also agree with the Steelwork Contractor and then instruct under the contract appropriate repairs to be completed on any defects that have been found.

The occurrence of LMAC depends upon a range of factors coming together at the same time. These factors derive from the design and detailing of the component, the condition and quality of the steel, detailing and fabrication and the galvanizing process. The weighting of the individual contributions from each of these activities is not known and no single factor, at this time, can be identified as the major contribution to LMAC. By following the guidance given in this document and by committing a modest amount of attention to detail at each stage of the construction process the chances of LMAC occurring can be substantially reduced.

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ANNEX A – Example Welding Procedure Specification (WPS)

W.P.S No: 1 **Revision:** 0

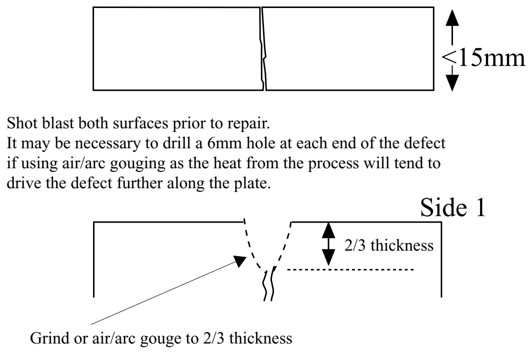
W.P.A.R No: BW-164-Rev. B

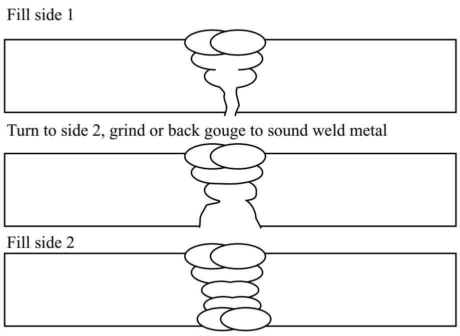
Contract No:

Project:

Joint Location: Repairs to deck, side plates and end plates.

Joint Design Welding Sequence





Welding Details:

Run	Process	Size of filler metal	Current A	Voltage V	Type of current/ Polarity	Wire Feed Speed	Travel Speed + mm/min
Side 1							
Root	F.C.A.W	1.2 mm	180/200	18/20	DC +	N/R	250-350 min
Remainder	F.C.A.W	1.2 mm	200/220	23/24	DC +	N/R	350-450 min
Turn to side 2 Back gouge or grind to sound weld metal mpi if required							
Side 2	F.C.A.W	1.2mm	200/220	23/24	DC +	N/R	350-450 min

Filler Metal Brand/Type: Filarc PZ6113/Fluxfil 14HD
Shielding Gas Type: Argoshield Heavy
Flow Rate: 15-20 L.P.M
Pre-heat temp (Min): 5 deg °C
Interpass temp (Max): 250 deg °C
Maximum weave: Stringer only
Details of backgouging/Backing: Air/arc or grind
Position: All except vertical down
Issued by: Date:

ANNEX B – Check list for Controlling LMAC

This check list covers the more important variables which affect critical decisions on the successful use of hot dip galvanizing. It should be used as a general guide.

1. STEEL TYPE (see Section 6.2)

a. Grade: S275, S355
b. Chemistry restriction: Silicon
c. Carbon equivalent/hardness

2. QUALITY OF ZINC (see Section 6.4)

Level of impurities

3. SIZE OF SUB-ASSEMBLIES AND ABILITY TO DIP IN THE BATH

Advice on galvanizing can be obtained from:

Galvanizers Association
56 Victoria Road
Sutton Coldfield
West Midlands
B72 1SY
Tel: +44(0) 121 355 8838
Fax: +44 (0) 121 355 8727
E-mail: ga@hdg.org.uk
Website: www.galvanizing.org.uk

4. DETAILING OF COMPONENTS FOR GALVANIZING (see Sections 6.1 and 6.3)

5. DISCUSSION BETWEEN ENGINEER AND GALVANIZER

Optimum solutions for hot dip galvanizing of structural steelwork especially for complex or novel sub-assemblies will be best achieved by discussion and co-operation between the Engineer and the galvanizing contractor.

6. INSPECTION STRATEGIES: POST GALVANIZING (See Section 4.0)

a. 100% visual
b. 100% visual and 100% MPI for vulnerable statically determinate structures
c. 100% visual and reduced level of MPI related to nature of structure and local criticality

ANNEX C – Examples of LMAC

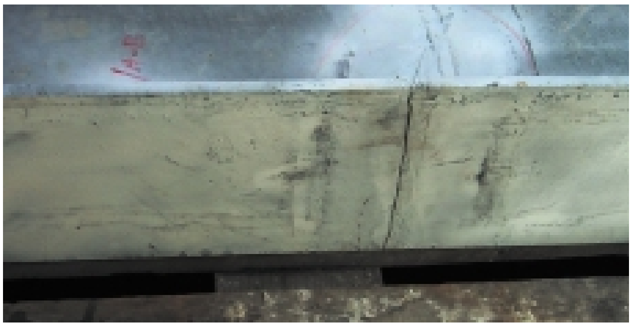


Figure C.1 Crack in the bottom flange of a beam (Courtesy Sedlacek, G., Dahl, W,. Hoffmeister, B., Kuhn, B., Feldmann, M., Pinger, Th., Langenberg, P., Eichenmuller, H., Grotmann D., Blum, M. 'Zur Sicheren Anwendung feuerverzinkter Stahltrager', Stahlbau 73 (2004), Heft 6, Page 427-437, Ernst & Sohn Verlag, Berlin.)

Figure C.2 Crack initiating from Cope (Courtesy Sedlacek, G., Dahl, W,. Hoffmeister, B., Kuhn, B., Feldmann, M., Pinger, Th., Langenberg, P., Eichenmuller, H., Grotmann D., Blum, M. 'Zur Sicheren Anwendung feuerverzinkter Stahltrager', Stahlbau 73 (2004), Heft 6, Page 427-437, Ernst & Sohn Verlag, Berlin.)

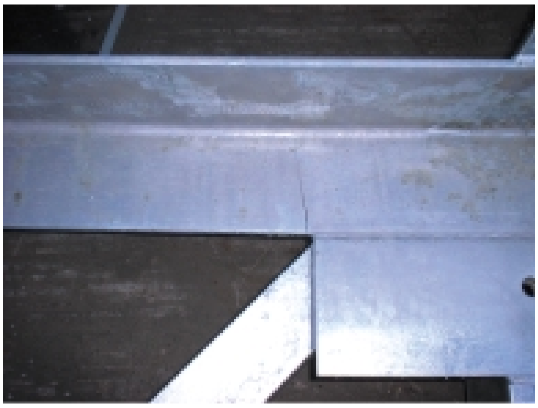


Figure C.3 Crack initiating from weld
(Courtesy of Mr. W Smith, Galvanizers Association)

Figure C.4 Crack initiating from gas-cut corner

Figure C.5 Crack initiating from weld

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