Front. Struct. Civ. Eng. 2019, 13(1): 49–65
https://doi.org/10.1007/s11709-017-0448-0

REVIEW

Hot-dip galvanizing of cold-formed steel hollow sections: a state-of-the-art review

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ABSTRACT A good understanding of the effects of galvanizing on the short- and long-term behaviours of steel components is essential for structural design. This review paper is motivated by a series of recent reports on cracking in galvanized cold-formed tubular steel structures and the limitations of current steel product standards and steel design specifications in this field. The steel-related and galvanizing-related factors, different pre-galvanizing countermeasures for brittle cracking and the available technical documents are summarized. An extensive bibliography is provided as a basis for future research and development in this field.

KEYWORDS cold-formed steel, hollow structural sections, hot-dip galvanizing, embrittlement, heat-treatment, residual stress, cracking

1 Introduction

Infrastructure is central to every aspect of our lives. Premature deterioration of civil infrastructure and repair of damage are multi-billion dollar problems. For example, the direct cost of metallic corrosion in the United States is approximately $276 billion per year, corresponding to 3.1% of the national gross domestic product [1]. Hence, corrosion protection is of paramount importance to exposed steel structures such as bridges, industrial plants, transmission towers and costal structures, because corrosion costs money, jobs and even lives. Among different techniques, hot-dip galvanizing is a cost-effective measure for corrosion protection. Galvanized steel structures are often maintenance-free since the service life of the zinc coating generally exceeds the design life of the structure it protects [2]. In addition, the shiny appearances of galvanized steel structures, such as the iconic VIA 57 West building in New York, are appreciated by many architects.

As shown in Figure 1, the complete galvanizing process includes three basic procedures: (1) surface preparation (degreasing, rinsing, pickling, rinsing and fluxing); (2) dipping of steel in the molten zinc bath; and (3) inspection. A hot alkali solution is often used during degreasing to remove dirt, paint marking and oil from the metal surface. The subsequent pickling process removes mill scales and oxides by dipping the steel in a dilute solution of hot sulphuric acid. Fluxing is the final surface preparation step in which a protective layer is created on the steel surface. This layer also promotes bonding between zinc and steel. The zinc bath, consisting of a minimum 98% pure liquid zinc, is typically maintained at 450°C. Structural components are immersed in and withdrawn from the bath slowly to ensure the quality of coating [2,3]. The appearance, toughness and thickness of the coating predominantly depend on the chemical compositions of the zinc bath and the steel [4].

Galvanized steel structures have numerous advantages in economical, environment protection and energy-saving aspects. Hence, a good understanding of the effects of galvanizing on the short- and long-term behaviours of steel components is essential for structural design. For example, the final hot-dipping process is certainly capable of inducing a significant thermal gradient through the steel component. Cracking of steel during galvanizing as a result of high residual and thermal stresses, as well as strain ageing-induced material embrittlement as a result of cold-

Article history: Received May 21, 2017; Accepted Jun 18, 2017

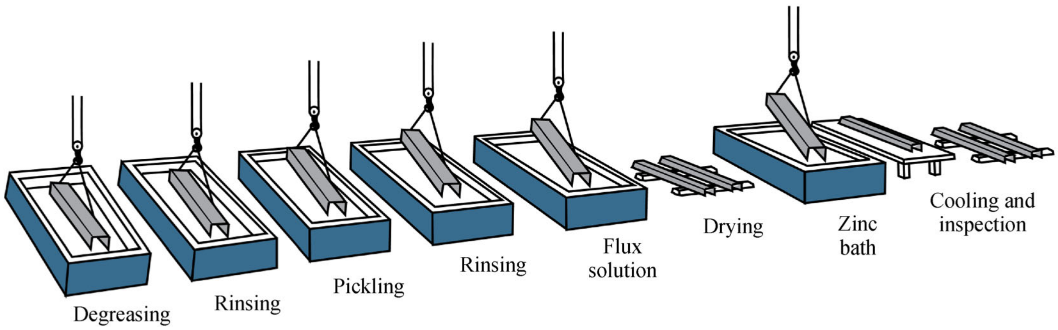

Fig. 1 Hot-dip galvanizing procedures [2]

forming and elevated temperature have been observed since the 1930s. The development of guidelines for prevention of cracking and significant embrittlement has since then been the focus of various research projects. A synthesis study of these early research projects can be found in an investigation conducted by the American Institute of Steel Construction [4]. Standards have been developed for safeguarding against cracking, embrittlement, warpage and distortion of steel components in North America [5–7] based on these early experimental investigations using the steels available in the 1950s. Similar standards and guidelines have been published in other parts of the world [3,8,9]. For many years, these standards have served well.

However, the embrittlement problem has resurfaced in the past decade. For example, premature cracking in galvanized highway structures has been reported across North America [10–15]. These cracks have caused some early decommissions and even hazardous collapses which present a great threat to public safety. Poor in-service performance of some galvanized steel structures has become an issue in Europe as well, hence the Eurocodes are attempting to develop provisions to address the problem [16]. These recently reported problems have attracted a lot of attention in both the industry and academia since galvanized steel structures are virtually everywhere. It was found that the reported premature cracking problems were in general coincident with the application of material of high strength and sections with large wall thickness, as well as new zinc bath mixtures with tin and bismuth added to enhance the quality of coating, which will be discussed in detail in the following sections. Hence, new guidelines for the prevention of significant embrittlement of modern steels during galvanizing need to be developed because the existing standards were developed based on steels available in the 1950s.

This review paper focuses on galvanized cold-formed steel Hollow Structural Sections (HSS). It is motivated by: (1) a series of recent reports on cracking in the corner regions of cold-formed Rectangular Hollow Sections (RHS) after galvanizing (see Figure 2 for examples); (2) concerns with the effects of galvanizing on the long-term and dynamic performances of cold-formed tubular steel structures; and (3) limitations of current steel product standards and steel design specifications in this field.

The occurrence of steel cracking during hot-dip galvanizing depends on: (1) steel-related factors such as steel chemistry, material properties, residual stress, and pre-galvanizing microcracks as a result of cold-forming; and (2) galvanizing-related factors such as degree of pickling, preheating, bath temperature, immersion rate and bath chemistry [4]. This paper reviews only those factors that affect galvanized cold-formed HSS. The steel-related and galvanizing-related factors, as well as the current practices for prevention of brittle cracking, are discussed in Sections 2 and 3. Different pre-galvanizing countermeasures for brittle cracking are compared in Section 4. Recent research in this field and their limitations are elaborated in Section 5.

2 HSS material-related factors

2.1 Steel chemistry

The appearance, thickness, strength and durability of zinc coating depend on the chemistries of the steel and the zinc bath. The effects of certain elements in steel on the coating structure have been studied extensively and incorporated into the galvanizing standards [4]. For example, to ensure the quality of coating, ASTM A385 [7] recommends the following steel composition: C$\leqslant$0.25%, Mn$\leqslant$1.3%, P$\leqslant$0.04%, Si$\leqslant$0.04% or 0.15%$\leqslant$Si$\leqslant$0.22%. The bath temperature and immersion time do influence the quality of the zinc coating obtained, but the most critical factor is the steel chemistry and in particular the silicon content. At typical galvanizing temperatures, the well-known "Sandelin curve" suggests that steels with silicon content less than 0.04% develop normal thin coatings. Excessively thick and brittle zinc coatings can be developed on "reactive steels" with silicon content from 0.04% to 0.15%. Acceptable coatings are produced when silicon levels range from 0.15% to 0.22%. For "reactive steels" with silicon higher than 0.22%, coating thickness continues to increase as the


(a) (b) (c)

Fig. 2 Examples of cold-formed RHS corner cracking during galvanizing. (a) Vancouver, Canada, 2016; (b) Vancouver, Canada, 2003 [11]; (c) Malaysia, 2009 [11]

silicon level increases [4]. Requirements on silicon content based on the “Sandelin curve” have been incorporated into the new ASTM standard for cold-formed HSS [17] (see Table 1) as well. The effects of zinc bath chemistry will be discussed in Section 3.3.

In the last decade the incidence of corner cracking of RHS has increased in North America and Asia, particularly during hot-dip galvanizing, where the problem has been generally attributed to liquid metal embrittlement (LME) in association with very high residual stresses in the corner regions [11]. LME is a phenomenon where certain ductile metals (e.g., structural steel) experience a significant loss of ductility or even undergo brittle fracture when exposed to specific liquid metals (e.g., zinc bath mixture). In general, a critical level of tensile stress on the surface of solid metal is needed for the liquid metal to penetrate and weaken the grain boundaries of the immersed solid metal [3,4,18,19]. The phenomenon of LME will be further discussed in Section 3. It should be noted that LME is only one type of the embrittlement and cracking mechanisms during galvanizing. The other types will be discussed in Section 3.

A useful concept for prevention of cracking during welding of carbon and alloy steels is the carbon equivalent (CE) which reduces the number of significant chemical compositional variables affecting the weldability of steel into a single quantity. Empirical carbon equivalent formulae, including carbon, manganese, silicon, nickel, vanadium, molybdenum and sometimes copper and boron contents, have been developed based on experimental investigations to control cracking of different types of steels during welding. Review of these experimental investigations can be found in Refs. [20,21].

The same approach has been used to minimize the risk of cracking in steel during galvanizing since carbon equivalent has been shown by previous research to have a strong link to the susceptibility of steel to LME [3]. For example, early research in Japan for the development of a new steel grade with low susceptibility to LME for application in power transmission towers [22] established Eqs. (1a) and (1b) for crack prevention:

$$\mathrm{CE} = \mathrm{C} + \frac{\mathrm{Mn}}{13} + \frac{\mathrm{Ni}}{29} + \frac{\mathrm{Cr}}{17} + \frac{\mathrm{Nb}}{7} + f(\mathrm{B}) \leqslant 0.22 \quad (1a)$$

where

$$f(\mathrm{B}) = \begin{cases} 0, & \mathrm{B} < 0.0005 \\ 0.04, & \mathrm{B} \geqslant 0.0005 \end{cases} \quad (1b)$$

The validity ranges of the above equations are as follows:

C: 0.02%~0.16%, Si: 0.10%~0.50%, Mn: 0.80%

~2.00%, Cu: 0%~0.40%, Ni: 0%~0.50%, Cr: 0%~0.60%, Mo: 0%~0.50%, Nb: 0%~0.10%, V: 0%~0.10%, B: 0% ~0.0010%.

Later, using a similar approach Abe et al. [23] studied cracking in galvanized steel bridges. Different carbon equivalent formulae for different steel types were proposed for prevention of LME. One of the formulae, which has been adopted in the Japanese standard for high-strength steel for application in transmission towers, JIS G3129 [24], is shown as follows:

$$\mathrm{CE} = \mathrm{C} + \frac{\mathrm{Si}}{17} + \frac{\mathrm{Mn}}{7.5} + \frac{\mathrm{Cu}}{13} + \frac{\mathrm{Ni}}{17} + \frac{\mathrm{Cr}}{4.5} + \frac{\mathrm{Mo}}{3} + \frac{\mathrm{V}}{1.5} + \frac{\mathrm{Nb}}{2} + \frac{\mathrm{Ti}}{4.5} + (420)(\mathrm{B}) \leqslant 0.44 \qquad (2)$$

The British guide for management of LME-induced cracking suggested the use of the above formula as well [3]. Although the validity range of Eq. (2) is not mentioned in JIS G3129 or the British guide, it should be noted that the above equation was developed based on experimental data on steels with carbon content below 0.12% [23]. A few similar formulae have been developed in other parts of the world but no attempt is made in this review paper to list all of them.

Table 1 shows the permitted amounts (by weight) of key ingredients, by cast or heat analysis, for popular grades of prominent HSS specifications. There are many similarities, other than the Australasian and the Chinese standards. ASTM A500 [25], the predominant American specification for cold-formed HSS, is notable for containing little prescription, particularly with regard to silicon which is essential for the production of high-quality zinc coating. For prevention of LME, careful control on the steel chemistry is important when the residual and thermal stresses are high, which is inevitable when galvanizing cold-formed steel products. However, it can be seen in Table 1 that the maximum permissible values of certain chemical elements in ASTM A500 are too liberal. For example, a 0.26% carbon content itself may invite LME problems based on Eq. 1(a). In addition, the ASTM A500 chemical requirements do not provide a sufficient recipe for LME prevention. As can be seen in Table (2), most of the input chemical elements in Eq. (2) are missing while research evidence [3,4] has shown that the presence of these missing elements can increase the possibility of LME, particularly the presence of boron. According to Eq. (2), a tiny amount of boron (B) will cause the CE-value to exceed the limit of 0.44. The chemical analysis results from six recent mill test reports from different North American tube manufacturers are listed in Table 3. It can be seen that the missing chemical elements such as Si, Cu, Ni, Cr, Mo, V, Ti and B are actually contained in the products. According to Tables 1 and 2, ASTM A1085 [17], CSA-G40.20/G40.21 [26], EN 10219-1 [27] and JIS G3466 [28] have similar problems as ASTM A500 [25]. It should be noted that steel products manufactured to these standards may be outside the ranges of validities of Eqs. (1a), (1b) and (2), as a result of the liberal maximum permissible values for certain elements.

China is now a major exporter of cold-formed HSS so their manufacturing standards should be of note. GB/T 6725 [29] and GB/T 6728 [30] are similar to EN10219-1 [27] and EN10219-2 [31], respectively. Different from EN10219-1, GB/T 6725 covers cold-formed open sections as well. For chemical requirements, GB/T 6725 refers to a series of Chinese standards for base material for production of cold-formed HSS, including carbon steel for general structural applications GB/T 700 [32], structural steel for bridges GB/T 714 [33], high strength low alloy structural

Table 1 Chemical compositions (by weight) for cold-formed RHS of common grades

Standard	Grade	Chemical composition (cast or product analysis), %max unless specified otherwise														
		C	Si	Mn	P	S	Cr	Mo	Al	Ti	Cu	Nb	V	Ni	N	B
ASTM A500	B	0.26	–	1.35	0.035	0.035	–	–	–	–	–	–	–	–	–	–
	C	0.23	–	1.35	0.035	0.035	–	–	–	–	–	–	–	–	–	–
ASTM A1085	A	0.26	⩽0.04 or 0.15-0.25	1.35	0.035	0.035	–	–	⩾0.02	–	–	–	–	–	–	–
CSA-G40.20/ G40.21	350W	0.23	0.40	0.50-1.50	0.04	0.05	–	–	–	–	–	–	–	–	–	–
EN 10219-1	S355J2H	0.22	0.55	1.60	0.03	0.03	–	–	–	–	–	–	–	–	–	–
AS/NZS 1163	350L0	0.20	0.45	1.60	0.03	0.03	0.30	0.10	0.10	0.04	–	Nb + V = 0.11		–	–	–
	450L0	0.20	0.45	1.70	0.03	0.03	0.50	0.35	0.10	0.04	–	Nb + V = 0.11		–	–	–
JIS G3466	STKR490	0.18	0.55	1.50	0.04	0.04	–	–	–	–	–	–	–	–	–	–
GB/T 1591(1)	Q345A	0.20	0.50	1.70	0.035	0.035	0.30	0.10	–	0.20	0.30	0.07	0.15	0.50	0.012	–
	Q460C	0.20	0.60	1.80	0.030	0.030	0.30	0.20	–	0.20	0.55	0.11	0.20	0.80	0.015	0.004

(1) As discussed in Section 2.1, GB/T 6725 refers to a series of standards for the chemical requirements of the base material for production of cold-formed RHS, including GB/T 1591.

Table 2 Calculation of possible Carbon Equivalent using the maximum permissible value in steel product standards

Standard	Grade	Chemical elements for use in Eq. (2) (%)(1)											CE per Eq.(2)(2)
		C	Si	Mn	Cu	Ni	Cr	Mo	V	Nb	Ti	B	
ASTM A500	B	0.26	–	1.35	–	–	–	–	–	–	–	–	0.44
	C	0.23	–	1.35	–	–	–	–	–	–	–	–	0.41
ASTM A1085	A	0.26	0.25	1.35	–	–	–	–	–	–	–	–	0.45
CSA-G40.20/ G40.21	350W	0.23	0.40	1.50	–	–	–	–	–	–	–	–	0.45
EN 10219-1	S355J2H	0.22	0.55	1.60	–	–	–	–	–	–	–	–	0.47
AS/NZS 1163	350L0	0.20	0.45	1.60	–	–	0.30	0.10	0.11(3)	–	0.04	–	0.62
	450L0	0.20	0.45	1.70	–	–	0.50	0.35	0.11(3)	–	0.04	–	0.76
JIS G3466	STKR490	0.18	0.55	1.50	–	–	–	–	–	–	–	–	0.41
GB/T 1591	Q345A	0.20	0.50	1.70	0.30	0.50	0.30	0.10	0.15	0.07	0.20	–	0.79
	Q460C	0.20	0.60	1.80	0.55	0.80	0.30	0.20	0.20	0.11	0.20	0.004	2.61

(1) The chemical elements by %weight are the maximum permissible values from the standards.
(2) For chemical elements not included in the standards, a value of zero is used in the calculation of the Carbon Equivalent (CE) in Eq. (2).
(3) AS/NZS 1163 specifies a 0.11% maximum weight for Nb + V. This table assumes Nb = 0% and V = 0.11% for calculation of Carbon Equivalent in Eq. (2).

Table 3 Calculation of Carbon Equivalent using mill test reports

Mill test report	Chemical elements (%)											CE per Eq.(2)(2)
	C	Si	Mn	Cu	Ni	Cr	Mo	V	Nb	Ti	B	
#1	0.2	0.023	0.75	0.02	0.008	0.026	0.002	0.002	-	0.002	0.0(1)	0.31
#2	0.190	0.014	0.800	0.050	0.017	0.053	0.004	0.002	-	0.000	0.000(1)	0.32
#3	0.190	0.026	0.800	0.048	0.014	0.050	0.004	0.002	-	0.000	0.000(1)	0.32
#4	0.190	0.014	0.820	0.051	0.019	0.044	0.005	0.002	-	0.000	0.000(1)	0.32
#5	0.14	0.23	0.86	0.01	0.05	0.04	0.00	0.013	-	-	-	0.29
#6	0.14	0.24	0.87	0.01	0.05	0.003	0.00	0.003	-	-	-	0.28

(1) The mill test reports do not include enough numbers of significant figures for Boron (B). See Section 2.1 for discussion.
(2) For chemical elements not included in the standards, a value of zero is used in the calculation of the Carbon Equivalent (CE) in Eq. (2).

steel GB/T 1591 [34], stainless steel GB/T 3280 [35] and weathering steel GB/T 4171 [36]. It should be noted that GB/T 700 specifies carbon steel with a minimum yield strength up to only 275 MPa. For the production of the commonly used cold-formed HSS of grade Q345, GB/T 6725 refers to GB/T 714 and GB/T 1591 for base material in its Appendix A. GB/T 714 and GB/T 1591 contain a much longer list of chemical elements since they cover high-strength low alloy steels. The chemical requirements for the two standards are very similar. Hence, Table 1 only includes the commonly specified grades Q345A and Q460C from GB/T 1591 with minimum yield strengths of 345 MPa (quality grade A) and 460 MPa (quality grade C), respectively. Similar to the Australasian standard [37], most of the input chemical elements in Eq. (2) are specified in GB/T 1591.

Possible CE-values per Eq. (2) are calculated using the maximum permissible values in the above steel product standards in Table 2. For chemical elements not included in the standards, a value of zero is used in the calculation. It should be noted that this assumption may greatly underestimate the CE-values. It can be seen in Table 2 that almost all possible CE-values could exceed the 0.44 limit for LME prevention. In particular, the 0.004% boron limit in GB/T 1591 [34] permits an extremely high CE-value per Eq.(2). The CE-values per Eq.(2) are also calculated using the chemical analysis results from six recent North American mill test reports in Table 3. Although the CE-values in Table 3 are below the 0.44 limit, it should be noted that certain chemical elements are missing. For the reports including boron, insufficient numbers of significant figures are provided, since a boron amount of just 0.0003% will cause the CE-values to exceed the limit.

2.2 Material properties

Corner cracking during galvanizing can be avoided by using hot-finished RHS since these products have inherently better grain structure and mechanical properties as well as a low level of residual stress in comparison with their cold-formed counterparts. This is consistent with the findings of previous experimental investigations [4,11,38] which suggest that galvanizing-related factors do have an effect on steel cracking, but only on already-susceptible material.

Hot-finished HSS are primarily manufactured in the U. K., German, France and Brazil to EN 10210 [39,40], and the most common grade is S355J2H. This approach typically commences with a Circular Hollow Section (CHS) produced by cold-forming using the Electric Resistance Welding (ERW) approach. The circular shape is then heated to achieve full normalizing, to above the upper critical transformation temperature of 870 °C to 930 °C, and is formed to the desired shape in this condition. Good toughness and ductility can be achieved around the entire cross-section of the final product. Hence, RHS with small outside corner radii can be produced using this approach without having cracking problems. Note that CHS to this specification, with very large wall thicknesses and low diameter-to-thickness ratios, as used in bridges, are likely to be manufactured by the seamless hot-forming approach [11]. However, this approach produces CHS only. ASTM A501 [41] is the American specification for hot-finished HSS. It should be noted that this specification is only to facilitate the importation of hot-finished HSS from Europe since these products are not manufactured in North America. However, hot-finished HSS is either unavailable in much of the world or prohibitively expensive. Hence, HSS is far more commonly produced by cold-forming.

2.2.1 Cold-forming methods

In general, heavily cold-formed steels are susceptible to LME and strain ageing [3,11,16]. The two mechanisms may cause significant transient and permanent losses of material ductility during and after galvanizing. The details of the two mechanisms will be discussed in Section 3.2.

It is well know that cold forming causes strain hardening of the steel material, hence its yield and ultimate strengths increase while its ductility decreases [42–44]. With cold-formed RHS, the tightness of corner radii is critical when there is concern for RHS corner cracking during galvanizing [4]. Internationally, there are two common manufacturing methods for cold-formed RHS: direct-forming and continuous-forming. For both methods, the coil strip is progressively cold-bent into the desired shape by passage through a serious of pressure rollers, during which the rollers introduce a controlled amount of cold bending (depending on the sizes of the used rollers) to the coil strip, thus the mechanical properties are theoretically consistent in the longitudinal direction of the RHS product. However, some gradual variation in the longitudinal direction will occur – for both production methods – in practice due to the location of the final RHS member relative to the position in the hot-rolled coil material from which it was made.

The direct-forming process is illustrated in Figure 3(a) and includes: (1) roll-forming a coil strip directly into an open section with the desired rectangular shape; and (2) joining the edges of the open section by welding to form a closed rectangular shape. The continuous-forming process is illustrated in Figure 3(b) and includes: (1) roll-forming a coil strip first into a circular open tube; (2) joining the edges of the open tube by welding to form a closed circular shape; and (3) flattening the circular tube walls to form the desired rectangular shape. In North America, Europe, Japan and Australia the continuous-forming process is used almost exclusively (one exception being Bull Moose Tube in the U.S. which uses the direct-forming method). In China, the direct-forming technique has become the dominant manufacturing method for production of large-sized RHS. Mass production by this method started from 2005 and the RHS have been successfully used in the construction of Olympic stadiums, railway stations, power plants and bridges [45].

Although the appearance of the sections can be similar,

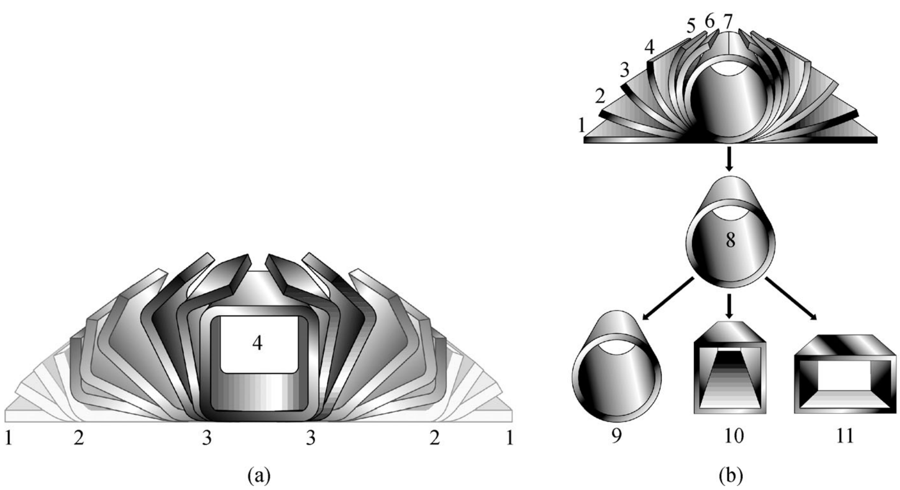

Fig. 3 Cold-forming methods. (a) Direct-forming; (b) Continuous-forming

the overall mechanical behaviours of RHS produced by different cold-forming methods can be substantially different. Extensive investigations have been conducted to capture the strength and ductility gradients around the cross-section of RHS produced by different cold-forming methods [e.g., 46–56]. For direct-formed RHS, the cold-working is concentrated at the four corners, thus the flat faces (not containing the weld) of the final RHS product have similar properties to the coil material. For continuous-formed RHS, the entire cross-section contains high degrees of cold-working, thus the final RHS product has higher yield and ultimate strengths and lower ductility compared to the coil material. However, if the same coil material is used, the mechanical properties of the corner regions of the direct- and continuous-formed RHS should be similar since the coil plates are bent to similar radii [57,58]. This deduction is consistent with the experimental evidences via tensile coupon tests [54] and Charpy V-notch impact tests [55]. Hence, for prevention of corner cracking during galvanizing, the key factor is the bending radius.

2.2.2 Relevant provisions in design guides for tubular steel structures

For prevention of cracking during welding, the ISO standard for welded hollow section connections under static loading [59] specifies minimum outside corner radii for welding in the zones of cold-forming without heat treatment (Table 4). As can be seen in Table 4, RHS manufacturing standards often permit much lower outside corner radii. Packer et al. [11] suggest that the ISO [59] corner radius recommendations may apply equally to galvanizing as both represent criteria affected by the extreme corner residual stresses induced by cold-forming. The Chinese technical specification for structures with steel hollow sections [60] also requires that special attention be paid to the corner properties of cold-formed RHS, especially when the structure is subject to seismic or fatigue loading. This specification suggests that when designing structures using cold-formed circular shapes, with wall thickness larger than 25 mm and diameter-to-wall thickness ratio smaller than 20, experimental investigations should be performed to study the cold-forming process, the mechanical properties of the section, the connection capacity as well as the risk of lamellar tearing. However, information on prevention of corner cracking in cold-formed RHS is limited in the Chinese specification.

2.2.3 Relevant provisions in HSS manufacturing specifications

HSS manufacturers are aware of this issue of potential cracking, but there is no definitive published guidance on this topic from structural steel associations [11]. The suitability of cold-formed RHS for galvanizing is generally avoided in HSS manufacturing specifications, or blanket statements are given such as in EN 10219-1 ..."the products shall be suitable for hot dip galvanizing" [27]. The Australasian [37] standard discusses suitability for hot-dip galvanizing, if galvanizing is required by the purchaser, and AS/NZS even goes as far as recommending that a sample be hot-dip galvanized to determine its actual performance for a given bath and tube characteristics. The problem with such a purchaser-driven approach is that most HSS produced internationally is sold to stock-holders, so the end user or fabricator does not usually interact with the manufacturer at the time of production [11].

In general, RHS with high yield-to-tensile strength ratios are susceptible to corner cracking. The minimum specified mechanical properties for cold-formed RHS of common grades are summarized in Table 5. It should be noted that the requirements are based on tensile test specimens machined from the flat face of the RHS in the longitudinal direction [61]. Hence, they are not directly relevant for assessment of susceptibility to LME and strain ageing. The yield-to-tensile stress ratios in Table 5 are calculated using the specified minimum values. However, in reality it is very difficult for manufacturers to achieve a yield-to-tensile stress ratio smaller than 0.85, even when such measurements are taken from the middle of a flat face where the degree of cold-forming is in general the lowest around the entire cross-section [11]. The yield-to-tensile stress ratio of the RHS corner material is in general higher than that of the material in the flat face [e.g., 46–50,52,54].

Kinstler [4] pointed out that the bending radius, is the most important single factor to consider when there is concern for brittle-type failure of steel galvanized after cold working. In general, the susceptibility to corner cracking increases as the RHS wall thickness increases and the corner radius decreases. The manufacturing ranges for outside corner radii of cold-formed RHS to different standards are summarized in Table 4. Similar to the ISO HSS connection design standard [59], the European standard for cold-formed HSS products [31] logically specifies *minimum* outside corner radii to avoid problems with welding or cracking in the corners of RHS. The Chinese standard [30] contains similar wall thickness thresholds and corner radius requirements. However, the predominant American standard for cold-formed HSS, ASTM A500 [25], together with the Canadian [26] and the Japanese [28] standards specify only *maximum* outside corner radii, due to an emphasis on achieving a reliably large "flat width" dimension. Measurements on contemporary RHS [54,62] showed a large spread of outside corner radius from 1.7t to 2.4t. To reduce the potential for corner cracking of RHS, during cold-forming and welding, the new ASTM A1085 standard for cold-formed HSS [17] specifies different minimum outside corner radii for different RHS wall thicknesses. However, the requirement

Table 4 Manufacturing requirements for outside corner radii of cold-formed RHS

Specification	RHS thickness, t (mm)	Outside corner radius, r_o	
		for fully Al-killed steel (Al$\geqslant$0.02%)	for fully Al-killed steel and C$\leqslant$0.18%, P$\leqslant$0.02% and S$\leqslant$0.012%
ISO 14346:2013[(1)]	$2.5\leqslant t\leqslant 6$	$\geqslant 2.0t$	$\geqslant 1.6t$
	$6 < t\leqslant 10$	$\geqslant 2.5t$	$\geqslant 2.0t$
	$10 < t\leqslant 12$	$\geqslant 3.0t$	$\geqslant 2.4t$ (up to t = 12.5)
	$12 < t\leqslant 24$	$\geqslant 4.0t$	–
EN 10219-2	$t\leqslant 6$	$1.6t$ to $2.4t$	
	$6 < t\leqslant 10$	$2.0t$ to $3.0t$	
	$t > 10$	$2.4t$ to $3.0t$	
ASTM A500	All t	$\leqslant 3.0t$	
ASTM A1085	$t\leqslant 10.2$	$1.6t$ to $3.0t$	
	$t > 10.2$	$1.8t$ to $3.0t$	
CSA-G40.20/G40.21	$t\leqslant 3$	$\leqslant$6 mm	
	$3 < t\leqslant 4$	$\leqslant$8 mm	
	$4 < t\leqslant 5$	$\leqslant$15 mm	
	$5 < t\leqslant 6$	$\leqslant$18 mm	
	$6 < t\leqslant 8$	$\leqslant$21 to 24 mm	
	$8 < t\leqslant 10$	$\leqslant$27 to 30 mm	
	$10 < t\leqslant 13$	$\leqslant$36 to 39 mm	
	$t > 13$	$\leqslant 3.0t$	
AS/NZS 1163	All t, up to 50×50 mm	$1.5t$ to $3.0t$	
	All t, larger than 50×50 mm	$1.8t$ to $3.0t$	
JIS G3466	All t	$\leqslant 3.0t$	
GB/T 6728 for $F_y > 320$ MPa	$t\leqslant 3$	$1.5t$ to $2.5t$	
	$3 < t\leqslant 6$	$2.0t$ to $3.0t$	
	$6 < t\leqslant 10$	$2.0t$ to $3.5t$	
	$t > 10$	$2.5t$ to $4.0t$	

(1) Requirements for welding in the corner regions of RHS without pre-treatment.

Table 5 Minimum specified mechanical properties for cold-formed RHS of common grades

Specification	Grade	F_y (MPa)	F_u (MPa)	F_y/F_u
EN 10219-1	S355J2H	355 for $t\leqslant 16$ 345 for $16 < t\leqslant 40$	510 for $t < 3$ 470 for $3\leqslant t\leqslant 40$	0.755 for $3\leqslant t\leqslant 40$
ASTM A500	B	315	400	0.788
	C	345	425	0.812
ASTM A1085	A	345	450	0.767
CSA-G40.20/G40.21	350W	350	450	0.778
AS/NZS 1163	C350L0	350	430	0.814
	C450L0	450	500	0.900
JIS G3466	STKR490	325	490	0.663
GB/T 6725	Q345	345	470	0.734

is still liberal compared to those in the European and ISO standards. According to the requirements in ISO 14346 [59] and EN10219-2 [31], producing to an outside corner radius of around 2t – for thicker-walled sections – is inviting corner cracking problems, unless there is careful control of the steel chemistry.

2.2.4 Relevant provisions in galvanizing standards

The occurrence of instant cracking in the corner region during galvanizing depends on the interaction of residual stress, thermal stress and the transient loss of ductility due to LME. The elevated temperature during galvanizing could potentially accelerate strain ageing and cause premature deterioration of the tubular member. However, the level of permanent loss of ductility depends on the pre-galvanizing degree of cold-forming [4].

To minimize the risk of LME and strain ageing embrittlement, the ISO galvanizing standard, ISO 14713-2 [9], suggests that local cold-forming should be kept as low as possible. Where the condition cannot be fulfilled, a pre-galvanizing stress-relieving by heat-treatment is recommended. However, the standard does not specify the heat-treatment temperature or duration. Similarly, the Australasian [8] and the Chinese [63] galvanizing standards as well as the British guide for management of LME-induced cracking (BCSA 2005) acknowledge that the elevated temperature during galvanizing can accelerate the onset of strain ageing embrittlement of cold-formed steel, and recommend stress-relieving to suppress this phenomenon, without specifying the temperature or duration for heat-treatment. However, experience in Canada [11] has shown that corner cracking can still occur with CAN/CSA-G40.20/G40.21 Class H RHS [26], which is stress-relieved to 450°C. In all, it is challenging to apply the provisions in the above galvanizing standard and guidelines since they are in general brief and qualitative.

The North American standard safeguarding against galvanizing-induced embrittlement, ASTM A143 [6], advises a minimum cold-bending radius of three times the plate thickness. Although ASTM A143 does not specify whether the limit is for the inside or outside radius of the cold-bent region, it has usually been interpreted as the inside radius [4]. For steel sections with smaller bending radii, different degrees of pre-galvanizing heat-treatment are recommended (see Section 4 for details). However, it is difficult to apply the provisions in ASTM A143 to modern cold-formed RHS since:

(1) The minimum cold-bending radius recommended by ASTM A143 conflicts with the corner radius requirements in certain production standards for structural steel tubing in North America (see Table 4). For example, ASTM A500 [25] requires that for RHS the outside corner radius shall not exceed 3t (i.e. three times the wall thickness t), corresponding to a maximum inside corner radius of 2t. The Canadian standard has similar requirements.

(2) The requirements in ASTM A143 were developed based on early research in the 1950s (reported by [4]) on the steels available at the time. Hence, the applicability to modern steel is unknown.

(3) Although ASTM A143 suggests heat-treatment of severely cold-formed steels for prevention of significant embrittlement and cracking, there is no definitive guideline on the thresholds of wall thickness above which different levels of heat-treatments are needed for tubular products (see Section 4 for details).

2.3 Residual stress

Also associated with cold-forming is the generation of residual stress. For the purpose of compression member design, residual stress in the longitudinal direction is much more influential than that in the transverse direction. The effect of longitudinal residual stress on the compression behaviour of a steel member is to cause premature yielding, leading to a loss of stiffness and a reduction in load-carrying capacity. In previous investigations on the compression behaviour of cold-formed RHS [e.g., 46,47,49,52,53,64], measurements of residual stresses have been conducted using the following methods:

(a) Destructive approach such as the sectioning method (see Figure 4(a));

(b) Semi-destructive approach such as the hole-drilling method (see Figure 4(b));

(c) Non-destructive approach such as the X-ray diffraction method (see Figure 4(c)).

The measured longitudinal residual stresses are commonly considered as two components. The first is the membrane component (tensile or compressive depending on the measuring location), which is the mean value of the measured longitudinal residual stress which occurs uniformly through the wall thickness. The second is the bending component, which is the deviation from the mean value. Due to the existence of the longitudinal residual stress, steel samples cut from the tube walls may exhibit both axial deformation and curvature, corresponding to membrane and bending residual stresses respectively. It can be concluded from the above investigations that the compression behaviour of cold-formed RHS is mostly affected by the bending residual stress, while the membrane residual stress plays a minimal role. The residual stress levels at the corner regions of direct- and continuous-formed RHS are similar since the corner radii are similar [53,54]. However, it should be noted that although extensive investigations on residual stresses in hollow structural sections have been conducted in the past, most of these investigations measured residual stresses in the longitudinal direction at the mid-length of the members since they are relevant to column behaviour. Investigation on residual stresses in the transverse direction of hollow structural sections is limited. Previous research [4,11,16,38], unpublished documents from Nippon Steel and Teck Cominco, as well as experience from galvanizers, has showed that cracking during galvanizing always starts at the inside surface of the corner region at the free end and propagates outwards through the tube wall and eventually down the tube length (i.e., in the longitudinal direction).

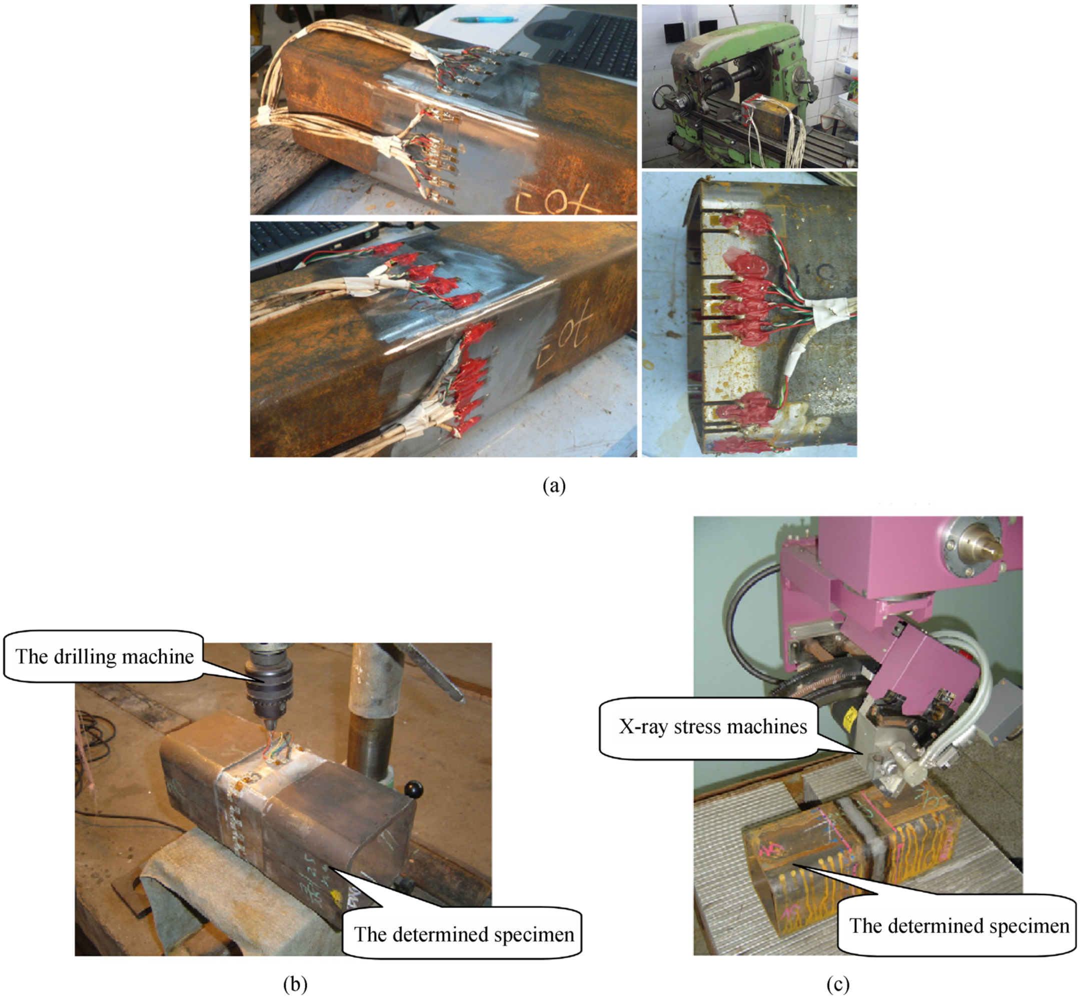

Fig. 4 Measurements of residual stresses in cold-formed RHS. (a) Sectioning method [64]; (b) Hole-drilling method [53]; (c) X-ray diffraction method [53]

Hence, measurements of residual stresses in the transverse direction at the free ends of cold-formed RHS are needed, and particularly in the corner regions.

2.4 Pre-galvanizing microcracks

The inside surface of RHS can sometimes contain crack-like fold-defects as a result of severe cold-forming [38]. These defects may become stress raisers during galvanizing and in turn make the steel products susceptible to cracking [4]. These defects also make it easier for liquid zinc and bath additives to penetrate the steel material and weaken the grain boundary.

Tolerances for local surface imperfections (such as gouges or grooves) are usually provided in HSS standards, typically as a percentage of the wall thickness, with permissible repair procedures. For example, ASTM 500 [25] suggests that surface imperfections shall be classed as defects when their depth reduces the remaining wall thickness to less than 90% of the specified wall thickness. The standard requires that the defect shall be completely removed by chipping or grinding to sound metal. However, microcracks in the corners of RHS – pre-existing in the coil material or produced during cold-forming of the RHS – are another issue that is not covered by HSS manufacturing specifications. The presence of such microcracks in the corners may have a dramatic influence if the section is subsequently subjected to hot-dip galvanizing. An investigation into surface defects of hollow sections by Chiew [65] recommended that sections with surface discontinuities (cracks) of depth greater than 0.2 mm, which are usually visible to the naked eye, be regarded as non-compliant sections and structurally defective. A problematic RHS specimen in an investigation on corner cracking of RHS during galvanizing [38], which will be discussed in Section 5, contained fold defects of a maximum depth of only 31 μm.

3 Effects of galvanizing

3.1 Thermal stress

When dipped in a molten zinc bath, compressive thermal stress is first developed on the surface of the steel section since the inner colder mass acts as a restraint on the expansion of the surface material. The differential expansion stress is reduced once the inner material starts to expand. The thermal stress on the surface becomes tensile when the steel section is withdrawn from the molten zinc bath since the surface material begins to cool while the contraction is restrained by the hotter inner material. Since tensile stress is necessary for the occurrence of cracking, steel sections are more susceptible to cracking when being withdrawn from the molten zinc bath [4,16,38]. Previous investigations [4,16] have suggested that cracking is triggered once the accumulative surface stress or strain (i.e., residual plus thermal) perpendicular to the direction of cracking reaches a critical value.

The thermal stresses developed on the surface of steel sections during galvanizing have been studied by researchers via site measurements and finite element simulations [e.g., 4,16,66,67]. It can be concluded that for typical galvanizing practices and commonly used steel sections, the maximum tensile thermal stress generated on the material surface can be up to 400 MPa, predominantly depending on the dipping and withdrawing speeds. Hence, severely cold-formed steels could be highly susceptible to cracking since they sometimes contain high levels of residual stress. In general, the induced thermal stress decreases as the dipping and withdrawing speeds increase. For example, Kikuchi and Iezawa [66] studied experimentally and numerically the thermal stresses at the weld toe of steel plate-to-pipe joints during galvanizing. It was found that the maximum thermal stress decreases as the dipping speed or the pipe diameter increases. Similar observation was made by Kominami et al. [67] in their study on thermal stress in steel pipes during galvanizing. However, it should be noted that it is not practical to change these speeds significantly for reactivity and drainage-control purposes.

3.2 Embrittlement and cracking mechanisms

Other than the thermal shock, steel materials may experience a transient or a permanent loss of ductility as a result of galvanizing. Depending on the characteristics and history of the steel, numerous types of embrittlement mechanisms may occur [3,4,16,18,19]. This paper discusses only the two embrittlement mechanisms relevant to structural steels of common grades: (1) liquid metal embrittlement, and (2) strain ageing. No attempt is made in this review paper to discuss the other mechanisms in details. For example, hydrogen embrittlement is a potential problem for high-strength steels with tensile strength greater than 1100 MPa, since the atomic hydrogen absorbed by high-strength steels during the pickling process can significantly reduce the ductility of the material. Identification of hydrogen trapping sites in metals and their participation in brittle fracture is an ongoing field of research. A literature review on this topic can be found in Ref. [19]. Quite often the heat of the galvanizing bath expels the atomic hydrogen absorbed by the steel during the pickling process. However, if the steel hardness is excessive, hydrogen can be retained and result in embrittlement [4,6,19]. Hence, when galvanizing high-strength steels and hydrogen embrittlement is of concern, pickling can be substituted by abrasive blast cleaning since the latter does not generate hydrogen [6]. Since structural steels of common grades are not susceptible to hydrogen embrittlement [3,4,18,19], it is not further discussed in the following sections.

3.2.1 Liquid Metal Embrittlement

One mechanism that may cause a transient loss of ductility in structural steel of common grades during hot-dip galvanizing is Liquid Metal Embrittlement (LME). LME occurs when steel is exposed to certain low-melting point liquid metals, such as zinc, while under tensile stress. Most descriptions of the LME phenomenon suggest that the occurrence requires an accumulative surface stress (i.e. residual stress plus thermal stress) beyond the elastic limit, at which point zinc penetration through grain boundary may occur. The material ductility decreases once intergranular decohesion takes place [3,4,18,19].

Motivated by reports on cracking of steel structures during galvanizing in Japan, Kikuchi and Iezawa [66] performed tensile coupon tests on steels of two different grades (SM50A and STK55). The tensile coupons were ruptured under different conditions:

Condition (a): at room temperature before galvanizing;

Condition (b): at the galvanizing temperature of 460 °C but in the absence of liquid zinc;

Condition (c): immersed in molten zinc bath maintained at 460 °C, and

Condition (d): at room temperature after galvanizing.

It was found that:

(1) The hot-dip galvanizing process has only a small effect on the initial portion of the stress-strain curve;

(2) The specimens immersed in molten zinc bath fractured much earlier than those under the other three conditions. The SM50A and STK55 specimens under Condition (c) fractured at 8.5% and 7.7% strains, respectively;

(3) The stress-strain curves of specimens under Conditions (a) and (d) almost overlapped; and

(4) The stress-strain curve from Condition (b) is below that of the base Condition (a), but the elongation before fracture remains more or less the same.

Similar observations were made in the experiments conducted by Kinstler [4]. Tensile tests were performed on steel coupons made from ASTM A36 steel (with a nominal yield strength of 250 MPa) at the galvanizing temperature of 450°C in the presence and absence of a molten zinc bath. It was found that the elastic portion of the stress-strain curve and the yield stress were not affected by the presence of zinc. However, the coupons immersed in the molten zinc bath fractured at a 5% strain, which is even earlier than that of Condition (c) in Kikuchi and Iezawa [66].

The results of the above investigations were consistent with the aforementioned general theory of LME. However, it should be noted that the steels tested by Kikuchi and Iezawa [66] were not heavily deformed before galvanizing. The ASTM A36 steel tested by Kinstler [4] had relatively low yield strength and good ductility as well. It can be expected that for severely cold-formed steel, such as the corner region of thick-walled cold-formed RHS, the material may brittle fracture at an earlier stage during galvanizing as a result of LME, high residual stresses, relatively low ductility and possible pre-galvanizing defects.

3.2.2 Strain ageing

Strain ageing is a mechanism that may cause a permanent loss of ductility of steel. It is associated with time-dependent diffusion of carbon and nitrogen atoms in the material. Carbon steel deformed to a critical degree may be embrittled significantly as a result of strain ageing. The resulting brittleness varies with the ageing temperature and time. At room temperature, the ageing process requires several months to obtain the maximum embrittlement [3,4,18,19]. However, the time for maximum embrittlement decreases significantly at elevated temperatures. For example, a high degree of strain ageing-induced embrittlement may occur in cold-formed steel when in contact with the 450 °C molten zinc bath. To account for the possible occurrence of the in-service ageing, the Australasian standard for cold-formed hollow structural sections AS/NZS 1163 [37] requires artificial "strain ageing" of the test pieces prior to tensile or impact testing, so that any change in HSS properties with time is likely captured by "strain ageing" the test samples. The ageing is achieved by heating to a temperature between 150 and 200 °C for not less than 15 min, which raises the yield stress and decreases the ductility.

3.3 Zinc bath chemistry

As discussed in Section 2.1, the quality of zinc coating depends on the chemistries of the steel and the bath mixture. The galvanizing bath typically contains 98% zinc and 2% additives [2,8]. Lead and aluminum have been traditionally added to the zinc bath to: (1) enhance the brightness of the galvanized coating; (2) suppress the over-reaction between zinc and steel with high silicon content to maintain a thin and ductile coating; and (3) enhance the drainage of molten zinc from the surface of the steel, and in turn to control the thickness and uniformity of the coating [4, 68–71). However, there has been ongoing pressure to remove lead from the zinc bath for environmental and health concerns [68].

Research has been conducted by dominant suppliers, such as Teck Cominco in Canada and Umicore in Belgium, on different bath additives and their impact on zinc coating quality [4,68]. It was found that Tin and Bismuth behave much like lead and aluminum in a zinc bath. They are effective in improving drainage, retarding the over-reaction between steel and zinc and enhancing the brightness of the coating, without the potential environmental impacts. As a result, new zinc bath mixtures with tin and bismuth have been developed (e.g., BritePlus™ by Teck Cominco and Galveco™ by Umicore).

However, the occurrence of steel cracking during hot-dip galvanizing seems to have become more prevalent since tin and bismuth were added to the zinc bath mixture [11,16]. According to the 2008 Nyrstar annual report, "between June 2000 and March 2007, Umicore produced and supplied (approximately) 45Kt of Galveco to galvanizers in various countries (corresponding to approx. 3.5Mt of steel that has been galvanized with Galveco). Umicore withdrew Galveco from the market in March 2007 as a precautionary measure following the discovery of cracking in steel that had been hot dip galvanized. It is alleged that a cause of this cracking is the use of Galveco." Similarly, in North America Teck Cominco was also blamed for its new product because the incidences of hot-dip cracking increased after the introduction of BritePlus™ [11].

Hence, Teck Cominco duly undertook some experimental research [38] into the galvanizing of contemporary RHS. It was found that the size of cracks became greater when the content of tin or bismuth exceeded approximately 0.2%. However, Teck Cominco concluded that the predominant factor affecting cracking upon galvanizing was the RHS itself, and that the zinc bath chemistry had only a small effect. Other details of this research will be discussed in Section 5. Criteria in an interim guidance document in Germany also include controls on tin and bismuth: $Sn + Pb \leqslant 1.3\%$ and $Bi \leqslant 0.1\%$ [3]. However, the document points out that "this is not an absolute limit below which either LME can be guaranteed not to occur or above which LME will definitely occur on a more then rare basis". Recently, as part of a research program for the evolution of Eurocode 3, Feldmann et al. [16] established different maximum plastic strain capacities for steel components based on the tin content in the zinc baths.

The details of the research by Feldmann et al. [16] are discussed in Section 5. However, it should be noted that the galvanizing process has been practiced for a century, with little change in practice. The new zinc bath composition has not been universally adopted while the issue of steel cracking during galvanizing has resurfaced internationally [4]. Hence, further research in this field is needed since, to this day, the relative significances of the steel-related and the galvanizing-related factors on the potential for LME and strain ageing have not been fully elucidated.

4 Countermeasures for embrittlement of steel during galvanizing

As discussed in Section 2.2.4, galvanizing standards [8,9,63] and industry guidance [3] commonly recommend pre-galvanizing stress relieving by heat treatment as a countermeasure for LME and strain ageing. However, the requirements in these standards are brief and qualitative. For example, the above standards do not specify the heat treatment temperatures and often suggest that "specialist advice should be sought".

In North America, post-cold forming heat treatment is available with ASTM A1085 [17] by specifying Supplement S1, and with CAN/CSA-G40.20/G40.21 [26] by specifying Class H. Both standards describe identical heat treatment, at a temperature of 450 °C or higher, followed by cooling in air. Although some HSS production plants have the ability to perform heat treatment on site, it usually involves transportation of the HSS to a third-party heat-treating facility. Ordering generally need to be done directly with a producer and, due to the extra processing required, a premium is applied to the selling price.

However, it should be noted that heat treatment at a temperature in the range of 450 to 480 °C does not affect the metallurgical properties to the extent of influencing the toughness. It has been shown, by laboratory testing, that such heat treatment does not provide any improvement in the Charpy V-notch (CVN) toughness of North American cold-formed HSS [55,72]. Similarly, experience in Canada [11] has shown that corner cracking can still occur with CAN/CSA-G40.20/G40.21 Class H RHS [26].

For steels roll-formed to a radius less than three times the plate thickness such as the corner regions of RHS, the ASTM document catering to prevention of LME and excessive strain ageing [6] recommends either normalizing the steel (870 °C to 925 °C) or stress relieving at a maximum of 595 °C, for 24 minutes per centimetre of section thickness, to avoid excessive grain growth. It should be noted that the normalizing process changes the grain structure of the material and produces HSS that are equivalent to hot-finished European HSS produced to EN 10210 [39,40].

As aforementioned in Section 2.3, cracking during galvanizing typically starts at the inside surface of the corner region at the free end. Research in Japan [73] found that the application of an anti-plating agent in the corner regions can effectively suppress LME since the susceptible material is no longer "wetted" by the molten zinc (see Figure 5). As can be seen in Figure 2, the RHS free ends tend to "open" during galvanizing as a result of high residual and thermal stresses in the transverse direction. Industrial experience from Nippon Steel & Sumikin Metal Products Co. Ltd., Japan [74] showed that the risk of cracking can be reduced by welding end plates to the RHS to restrain the expansion of the section. The end plates could be cut off after galvanizing. Grinding the inside corners at the member ends has also been found to be effective in improving crack resistance. This procedure helps to remove folds and other surface roughness that tend to act as stress raisers and crack initiation sites. It also probably removes some of the hardest and most brittle material at these locations [38].

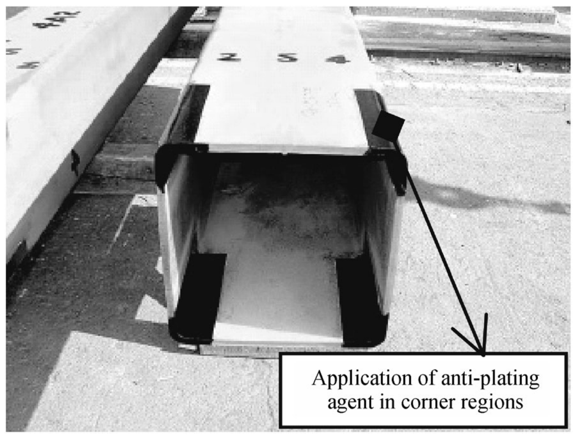

Fig. 5 Application of anti-plating agent to prevent corner cracking during galvanizing [73]

5 Recent research

Motivated by the lack of technical guidance for prevention of corner cracking of RHS, Poag and Zervoudis [38] performed a series of experiments on four RHS specimens of the same size (RHS 127×76×9.5 mm). The four RHS specimens were obtained from four sources, cut into short lengths and dipped into zinc bath mixtures with different amount of additives such as tin and bismuth. It was found that "susceptible" RHS specimens with high yield-to-ultimate stress ratios and pre-existing crack-like defects cracked in the corner regions in all zinc baths, while the less susceptible material did not crack at all. Hence, it was concluded that the zinc bath chemistry had a lesser effect, and only on susceptible steel material. The research conducted by Poag and Zervoudis [38] shed light on the RHS corner cracking problem. However, this research is highly qualitative due to its small scope. The four RHS specimens have the same cross-sectional dimensions. Hence, the thresholds of wall thickness above which different levels of pre-galvanizing countermeasures are needed could not be determined. The yield-to-ultimate stress ratio was obtained from mill test reports. Hence, the results were most likely from testing of tensile coupons machined from the flat faces of the RHS specimens, which are not representative of the material properties at the corner regions where the cracking occurred. It is unknown where the RHS specimens were manufactured. Pre-existing crack-like defects with a maximum depth of 31μm were found in a cracked RHS specimen. Although the research acknowledged that RHS containing high levels of residual stress are more susceptible to cracking, no residual stress measurements were performed.

Funded by Departments of Transportation across the country, a series of investigations has been conducted in the United States to explain the poor in-service performance of some recently built galvanized steel highway structures [10,12–15]. One of the key research parameters is the cold-bending radius of the steel components. However, the components tested, such as high mast illumination poles, generally have very large bending radius-to-thickness values which satisfy the ASTM A143 limit. Hence, the research outcomes do not apply to cold-formed RHS.

Similar research has recently been conducted by the Joint Research Centre of the European Commission [16] for the evolution of Eurocode 3. Technical guidelines were developed to help minimize the risk of cracking of modern steel during galvanizing. However, this research only included slightly cold-formed members such as pre-cambered beams before hot-dip galvanizing. It assumes a maximum cold-forming-induced plastic deformation (ε_{pl}) of 2%, which can be calculated using Eq. (3).

$$\varepsilon_{pl} = \frac{t}{2r_{\mathrm{i}} + t} \tag{3}$$

where t is the plate thickness, and r_{i} is the inside radius of cold-forming.

Hence, the guidelines proposed by Feldmann et al. [16] in general do not apply to cold-formed RHS. For example, using Eq. (3) and assuming an inside radius of t, the plastic deformation on the inside surface of the corner region of a cold-formed RHS is 33%. Same as ASTM A143 [6], Feldmann et al. advise the application of heat-treatment for high degrees of cold-forming. In addition, Feldmann et al. assume notch-free surfaces, while Poag and Zervoudis [38] suggest that crack-like fold defects could sometimes be generated as a result of severe cold-forming. These defects may become stress raisers during galvanizing and in turn make the steel products susceptible to cracking. It can be concluded from the literature review that research in effects of galvanizing on cold-formed steel tubing is limited at present.

6 Conclusions

Whether structures made of modern steel sections of different strengths and sizes can be critically embrittled during galvanizing is difficult to research since the occurrence depends on the interaction of many factors including the quality of steel, structural design and detailing, fabrication as well as the galvanizing process. This review paper provides a basis for future research on: (1) the prerequisites for cracking of cold-formed RHS; (2) the effect of cold-formed RHS cross-section geometry on galvanizing-induced embrittlement; (3) the thresholds of cold-formed RHS wall thickness above which different levels of pre-galvanizing countermeasures are needed; and (4) the detrimental/beneficial effects of hot-dip galvanizing on the mechanical behaviours of cold-formed RHS.

Acknowledgements The authors would like to acknowledge the financial support from the Canadian Institute of Steel Construction (CISC) and the Natural Sciences and Engineering Research Council of Canada (NSERC).

Symbols and Abbreviations

r_{i}	inside corner radius
r_{o}	outside corner radius
t	wall thickness
A	cross-sectional area
CHS	circular hollow section
CE	carbon equivalent
E	modulus of elasticity
ERW	electric resistance welding
F_y	yield stress
F_u	tensile strength
HSS	hollow structural section
I	moment of inertia
K	column effective length factor
L	unsupported length of column
LME	liquid metal embrittlement
RHS	rectangular hollow section
ε_{pl}	plastic deformation

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