Liquid Metal Embrittlement of Galvanized Steels During Industrial Processing: A Review

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Abstract Liquid metal embrittlement is the cause of reduction of elongation to failure and early fracture if normally ductile metals or alloys are stressed while in contact with liquid metals. Scientists have confirmed that many solid steel-liquid metal couples are subject to liquid metal embrittlement, one of them is solid steel-liquid zinc. Due to the wide use of zinc-coated galvanized steels, this couple has drawn much attention. This paper briefly introduces liquid metal embrittlement, with emphasis on the solid steel-liquid zinc couple and its occurrence in the process of industrial production in the literature. We first reviewed the findings that galvanized steels suffer embrittlement during experimental hot tensile test to understand its fundamental characteristics. We then summarized the occurrence of liquid metal embrittlement in galvanized steels during industrial processing, such as hot-dip galvanizing, hot stamping and welding.

Keywords Liquid metal embrittlement · Galvanized steel · Hot tensile test
Hot stamping · Welding

1 Introduction

Liquid metal embrittlement (LME), also known as liquid metal induced embrittlement (LMIE) or liquid metal assist cracking (LMAC), is the reduction on elongation to failure and early fracture if normally ductile metals or alloys are stressed while in contact with liquid metals [1]. Cracking arises in LME is classified as one case of environmental assist cracking (EAC). Although causing a lot of

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troubles in practice, the phenomenon is not fully understood compared with some other EAC, such as hydrogen embrittlement and stress corrosion cracking. According to a review paper [2], the earliest study of LME was published in 1914, in which the internal stressed brass was fractured when in contact with mercury was discussed. Up until now, LME has been studied for over a century, the existing scientific paper which concerns the susceptibility of various specific combinations to LME is plentiful but dispersive [3]. Scientists have been dedicated to find out a universal mechanism to explain all the LME phenomenon and predict its occurrence, and several modes have been proposed [1–3]. The most recent contribution was done by Bauer et al. [4], in which they combined density functional theory calculations with thermodynamic considerations to investigate the LME of iron by liquid zinc. Nevertheless, none of them can fully account for all experimental observations.

Generally, several features are widely accepted for LME:

(a) Particular solid metal-liquid metal couples are prone to LME, which means some couples are susceptible to embrittlement while others appear to be immune. This is referred to as the specificity of LME.
(b) A critical stress is required for the occurrence of LME, and the liquid metal must direct contact on an atomic scale with the stressed solid metal.
(c) LME results in initial intergranular and brittle fracture in most cases for the polycrystalline metal and alloy.
(d) A specific brittle-ductile transition temperature always exists in LME for different embrittling couples.

Among all the materials, steels own a dominant position for industrial use due to their abundant source, economic efficiency and comprehensive performance. Thus, numerous studies focused on the LME of various steels and they are proved to have a poor resistance to LME. Due to the serious condition which satisfies the prerequisites, LME of steels is frequently reported under the circumstance of nuclear applications, as they can be embrittled by liquid Pb-17Li [5], Pb [6], or Pb–Bi eutectic [7] in service. Under experimental condition, steels can also be embrittled by Cu [8], Na [9], Sn [10] and so on. Recently, a clutch shell of a motorbike made from SPCC nitrided steel [11] and turbine casing segment screws of an aeroengine made from 35NC6 steel [12] are reported to suffer LME, indicating LME phenomena extensively exist in actual use.

Empirical rules suggest that an embrittlement couple may have limited mutual solubility and low tendency to form stable intermetallic compounds (IMCs) [3], in contrast with the rules, zinc can embrittle steel, even if they have relatively good mutual solubility and can form stable IMCs, as can be seen in Fig. 1. For over 200 years, the zinc coating is widely used to provide corrosion resistance for steel, it can separate the steel from the corrosion environment and act as the sacrificial anode [14]. From the perspective of LME, zinc coating provides the potential liquid metal film so that LME may occur in steel if the temperature and stress conditions meet the prerequisites of LME. The melting point of zinc is low (about 419 °C),

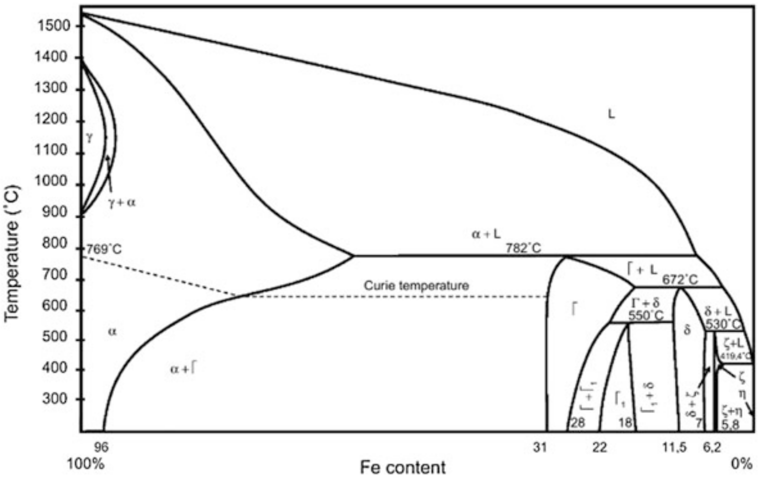


Fig. 1 Iron–Zinc binary diagram [13]

and as expected, galvanized steels are susceptible to LME cracking phenomena when they are subjected to some hot industrial processes such as hot-dip galvanizing, hot stamping and welding according to opening literatures. This paper gives a brief review of these literatures and try to offer a comprehensively understanding of LME phenomena of galvanized steels during industrial processes.

2 LME of Galvanized Steels During Hot Tensile Test

When doing research on LME of various embrittlement couples, materials scientists always carry out hot tensile test to obtain the data characterizing the phenomena, and nowadays, hot tensile tests are often performed using a Gleeble thermo-mechanical simulator. The experiment can provide ideal and quantitative conditions in laboratory, while stressed specimens are in contact with liquid metal under certain strain rate and temperature. Thus, for the solid steel-liquid zinc combination, this test method is also frequently used. Some of the achievements about LME of steel by zinc were reported in Japanese language papers many years ago [15–19]. In this section, a few recent papers using hot tensile test to study liquid zinc embrittlement on steels are introduced previously to help understand the embrittlement phenomenon. Several factors were found to have influence on the LME.

Beal et al. [20–22] studied the LME of electrogalvanized (EG) twinning-induced plasticity (TWIP) steel, the steel is fully austenitic at room temperature, and the contact with liquid zinc was due to the melting of the zinc coating. Figure 2 shows the tensile curves of uncoated and EG steels at different temperatures under a strain

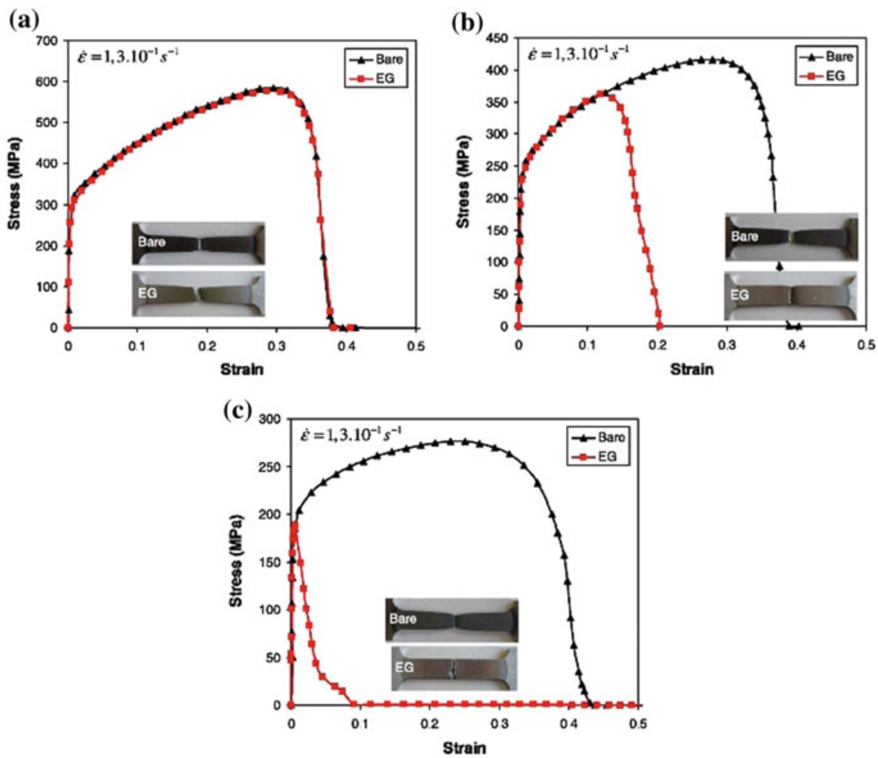


Fig. 2 Tensile curves of bare and electrogalvanized (EG) specimens obtained at different temperatures: **a** 600 °C, **b** 700 °C and **c** 800 °C [22]

rate of 0.13/s. It can be seen that the EG specimen was not embrittled at 600 °C, but its ultimate tensile strength and fracture elongation reduce compared with uncoated one at 700 °C. The steel is more severely embrittled at 800 °C, as fracture occurs at a very small strain. It is worth noticing that the lower embrittlement temperature is much higher than the melting point of zinc, it may attribute to the experimental procedure where liquid zinc came from the melt of zinc coating, the fast process required higher temperature for zinc coating to be fully melted. It seems convincing as LME of steel by zinc were found to occur at about 450 °C in liquid zinc bath during galvanizing [23]. However, Barthelmie et al. [24] reported that the galvanized surface refined TWIP steel could be embrittled at 450 °C during hot tensile test. Frappier et al. [25] investigated the embrittlement of an EG advanced multiphase high strength steel which consists of ferrite/bainite matrix with about 12% of retained austenite, the test conditions were similar with Beal et al. and they obtained same LME starting temperature. They claimed that the beginning of

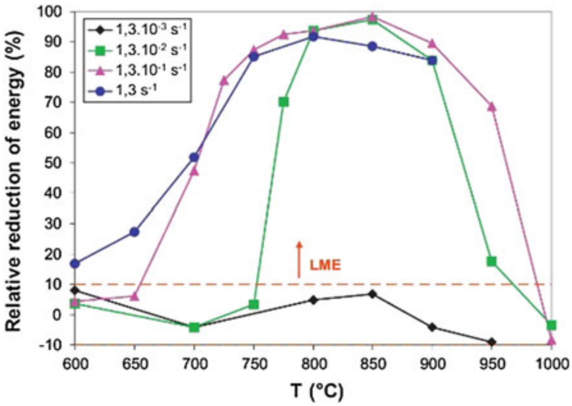


Fig. 3 Influence of strain rate on the embrittlement of the Fe22Mn0.6C steel by liquid zinc [21]

embrittlement at 700 °C was due to a wetting transition, the liquid metal can wet the grain boundary (GB) if

$$\gamma_{GB} > 2\gamma_{SL} \tag{1}$$

where γ_{GB} is the grain boundary energy and γ_{SL} is the solid steel-liquid zinc interfacial energy. Microscopic image of steel/Zn interface gave the evidence of GB wetting by Zn, so they believed the lower temperature for LME was the wetting transition temperature for steel/Zn couple, which explained why LME didn't occur at melting point of zinc. Figure 3 demonstrates the variation of relative reduction of energy as a function of the temperature for the four strain rates, it clearly indicates that at low strain rate (black line), no significant LME occurs at all test temperatures, and the higher the strain rate, the lower temperature at which the LME occurs. The graph also illustrates the "ductility trough" and "brittle-ductile transition" features which are commonly observed in many LME systems. The ductility of the steel was lost within a temperature range of 700–950 °C, and fully regained at about 1000 °C. Beal et al. [21] hypothesized that the recovery of ductility at high temperature is due to the evaporation of zinc, whose boiling point is about 907 °C, which makes the liquid zinc insufficient for embrittlement to occur. Figure 4 presents the influence of holding time in the LME, the specimens were pre-exposed to liquid zinc and maintained for a certain holding time before the tensile test. It can be seen that long holding time leads to a recovery of ductility, and when the holding time increases to 20 s, the tensile curve of EG specimen is highly coincident with uncoated one and the embrittlement is fully suppressed. Beal et al. [22] claimed that the formation of IMCs at the interface between steel and zinc was responsible for the recovery when increasing the holding time, as they prevented the contact of steel with liquid zinc.

Jung et al. [26] investigated the influence of constituent microstructure of the galvanized steel and pre-strain on the LME, three kinds of steels, i.e. deep draw quality (DQ) steel which consists of fully ferritic, dual-phase (DP) steel which

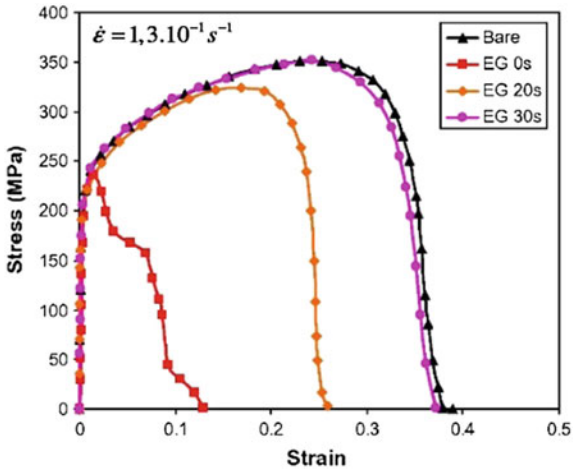


Fig. 4 Tensile curves obtained at 750 °C (strain rate 0.13/s): progressive ductility recovery after holding at 750 °C [22]

Table 1 Summarized results of hot tensile test to reveal LME occurring conditions of each alloy (orange colored box = ferrite, blue colored box = austenite) [26]

	Strain rate (s^{-1})	600 °C	700 °C	800 °C	900 °C
DQ	1			LME	LME
	0.1			LME	LME
	0.01			LME	LME
DP	1	LME	LME	LME	LME
	0.1		LME	LME	LME
	0.01			LME	LME
TWIP	1		LME	LME	LME
	0.1		LME	LME	LME
	0.01			LME	LME

consists of ferrite and martensite, TWIP steel which consists of austenite, were chosen to carry out the hot tensile test. The overall results on the occurrence of LME were summarized in Table 1. It proves that the occurrence of LME is irrelevant to the original microstructure of steel. Results also show that the temperature and strain rate have an influence on the LME, which is consistent with previous statements. Furthermore, under the conditions of temperature of 600 °C and strain rate of 0.1/s, no LME occurred, but DP and TWIP steels were embrittled under the same conditions after they were pre-strained up to 0.4% at 900 °C. Taking into account that the engineering strain of 0.4% just passed the yield point, the authors claimed that not only stress but also plastic deformation was needed for the occurrence of LME. With the help of TEM images and EDS line profiling results, they found that the pre-strain could accelerate zinc diffusion into substrate grain boundaries (GBs) as well as weakened them and subsequently caused the LME even at the conditions where LME normally did not occur.

Kang et al. [27] researched the LME of a Zn-coated Interstitial-Free (IF) steel, a Zn-coated 22MnB5 press-hardened steel (PHS) and a Zn-coated TWIP steel, and found that the PHS and TWIP steel suffered LME at 850 °C. But no LME occurred in IF steel at both 850 °C (below A_{c1} temperature) and 950 °C (above A_{c3} temperature), this indicated that the LME of steels was not directly related to their crystal structure but the composition and type of steel did influence the LME process. The LME occurred due to the penetration of Zn, and the average penetration depth of the IF steel, PHS and TWIP steel were 53, 152 and 303 μm respectively, which explained their differences in the LME behavior. The Zn percolation along GBs and rapid solid-state Zn grain boundary diffusion were proposed to be compatible with the Zn penetration process.

From the above statements, it can be concluded that the temperature, strain rate, pre-strain, and type of steel all influence the LME of steel by liquid zinc in different ways. Particular conditions needed for LME to occur can be experienced during hot working processes such as hot-dip galvanizing, hot stamping and welding. These have been confirmed by many researches and they will be discussed next.

3 LME of Steels During Hot-Dip Galvanizing

Zinc coatings are predominantly used to improve the corrosion resistance of steel, typical processing methods used in producing zinc coatings include hot-dip galvanizing (GI), galvannealing (GA) and electrogalvanizing (EG). For hot-dip galvanizing method, the steels are dipped into 445–455 °C molten zinc bath and the immersion times are in the range of 3–6 min [28]. Before hot-dip galvanizing, the steel surface is carefully cleaned to remove any impurities so that the steel substrate is directly in contact with liquid zinc during the hot-dip galvanizing process. LME cracking sometimes appear during hot-dip galvanizing in large structural steel components like beams and profiles, or welded structures, as shown in Fig. 5. Mraz and Lesay [29] concluded that the stress needed for the cracking came from local residual stresses as the consequences of welding and local strains as the

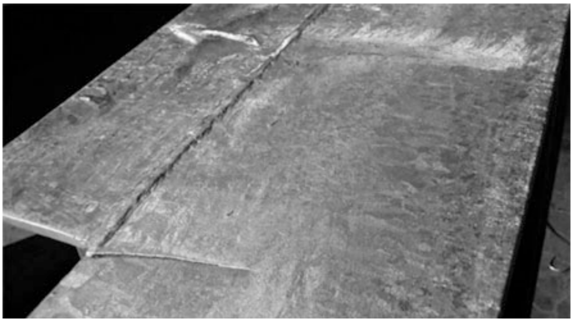


Fig. 5 Observation of LMAC in a steel structure after hot-dip galvanizing [13]

consequences of heating during galvanizing. Under the situation, James [30] suggested that a good design of structural steelworks can help against the LME during galvanizing.

To investigate the LME phenomena during galvanizing, scientists always apply external load to better present the results. Carpio et al. [31] researched how environmental factors acted in steel embrittlement during galvanizing, the structural S450J0 steel was chosen as the main study material, its low ductility and high strength made it very prone to suffer failure during galvanizing. Tensile and Charpy impact test results showed that the properties of studied steels dropped at 450 °C compared with that at room temperature, so the steel was softer and more brittle at galvanizing temperature, but it was not the main cause of the embrittlement during galvanizing. Fluxing treatment are always used to prevent oxidation before galvanizing. The study indicated that the fluxing increased the surface roughness so as to enhance the susceptibility of local embrittlement due to notch effect, which was related to stress concentration. Fluxing as well as galvanizing led to the hydrogen accumulation, it gave a possibility that the embrittlement might be caused by hydrogen. This hypothesis was denied also by Carpio et al. [32] in another paper, in which they tested and calculated the hydrogen concentration in the steel base and zinc layer and found that the hydrogen mainly presented in the zinc layer and hardly existed in the steel base. Nevertheless, Mraz and Lesay [29] complained that the hydrogen embrittlement was responsible for crack initiation and LME was responsible for crack propagation as they observed the transgranular fracture at crack initiation sites and intergranular fracture at crack propagation sites. J toughness tests were carried out on compact tensile specimens at 450 °C in air and two different Zn baths: traditional Zn–Pb bath and innovative Zn–Pb–Sn–Bi bath [31]. Results showed that the toughness of the samples further decreased in Zn bath and the embrittlement was more aggressive in the Zn–Pb–Sn–Bi bath, as shown in Fig. 6. It was because Sn and Pb were accumulated next to the steel base and

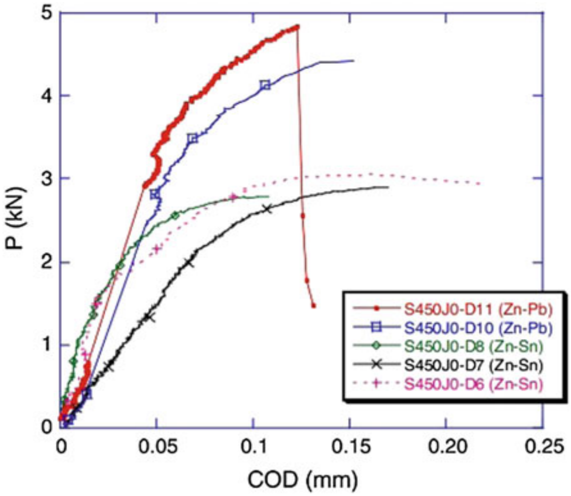


Fig. 6 Toughness J-test results on CT specimens made of S450J0 steel in two liquid Zn baths: Traditional (Zn–Pb) and Zn–Pb–Sn–Bi baths [31]

formed low-melting-point eutectics (about 180 °C, even less if Bi was present), they flowed easily to the cracks and were very reactive with the steel, thus facilitated the embrittlement process.

Mendala [23] applied tension stretching with different levels (400–800 MPa) to the C70D steel during hot dip galvanizing at 450 °C. Two liquid baths were used, i.e. pure zinc and zinc with 2% tin addition. Results showed that if the load was applied to the samples and suddenly released, no cracking occurred for all samples under different load values. If the constant load was applied to the samples during galvanizing, no cracking occurred in the samples that dipped in a zinc bath but cracking was detected in the samples during metallization in a zinc bath with 2% tin addition under high stress values, 600 and 700 MPa, and the sample was ruptured under 800 MPa. The author deduced that the constant load could let the internal stresses accumulate and the cracks would occur in liquid bath as a result of loss of cohesive properties. The explanation of the conducive effect of tin was not given in the paper, but as tin is a severe steel embrittler and the embrittlement can happen at 266 °C [10], the concept of "Insert Carriers" [3] may be introduced to explain the phenomenon.

The influence of previous cold deformation on LME of typical structural steel S235JR in 450 °C liquid zinc bath was studied by Luithle and Pohl [33]. The samples were firstly tested in 450 °C hot air, their tensile strength increased and reduction of area decreased with the increase of deformation degree owing to the work-hardening. Thus, the severity of LME was evaluated by the ratio of reduction in area of samples tested in 450 °C liquid zinc bath and 450 °C hot air under the same deformation degree. Results showed that the severity of LME decreased with the increasing degree of deformation, and the fracture surfaces changed from intergranular cleavages to ductile dimples. If the deformation was large enough, there were almost no difference between the samples tested in hot air and liquid zinc. The authors explained that with increasing cold deformation the grains became more and more stretched in axial direction, the original GBs (preferred intergranular crack paths) which were perpendicular to the applied force became more parallel to the load, and thus, the component stress was not enough to open the GB, leading to the removal of LME.

4 LME of Galvanized Steels During Hot Stamping

Hot stamping, also called press hardening, was developed in accordance with the demand for ultra-high strength steels in automobile industry. Currently, there are two different hot stamping methods, i.e. the direct hot stamping process in which a blank is heated up in a furnace, transferred to the press and subsequently formed and quenched in the closed tool, and the indirect process characterized by the use of a nearly complete cold pre-formed part which is subjected only to a quenching and calibration operation in the press after austenitization [34]. To protect the steels from oxidation and provide cathodic corrosion protection during hot stamping, the steels are often galvanized before the process. However, Zn-coated steels are easily

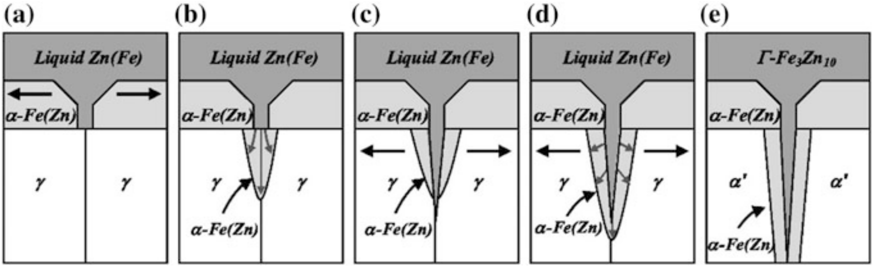


Fig. 7 Schematic illustrating the mechanism of Zn grain boundary diffusion-mitigated phase transformation leading to crack formation on Zn-coated PHS during die quenching (γ: austenite, α′: martensite) [37]

subjected to LME cracks during hot stamping process, especially the direct hot stamping process [35], which has potentially bad effect on the mechanical properties of the parts.

Lee and his coworkers published several papers about the LME of galvanized 22MnB5 during direct hot stamping simulated by a Gleeble 3500 thermo-mechanical process simulator. In one paper published in 2012 [36], they found that when the specimen was deformed at 850 °C, Zn penetrated into the steel matrix and caused brittle fracture due to grain boundary decohesion. The fracture didn't occur when the specimen was held at 850 °C for 4 min, quenched to 700 °C and deformed at this temperature. It was because that the solid Γ_1 intermetallic compound was formed as a result of a peritectic reaction between solid α-Fe and liquid Zn at 782 °C during quenching, and the absence of liquid Zn inhibited the LME. Increasing the annealing time, i.e. soaking at 850 °C to 20 min before hot stamping also suppressed the LME as the coating layer was fully transformed to α-Fe (Zn), no liquid Zn presented to cause LME in this case. In another paper published in 2014 [37], they gave a detailed mechanism for LME cracking during hot stamping, as illustrated in Fig. 7: (a) High-temperature crack initiation at an α-Fe(Zn) grain boundary in the surface alloy layer; (b) Zn diffusion along the γ grain boundary and transformation of the Zn-diffused γ grain boundary region to α-Fe(Zn); (c) Crack propagation through the weak α-Fe(Zn) grain boundary layer; (d) Crack propagation by repetition of the diffusion-transformation stages (b) and (c); (e) After cooling, the high-temperature Zn_{liq} distribution is reflected in the room-temperature distribution of Γ-Fe3Zn10. The absence of transformation of γ to α′ lath martensite allows for the identification of the Zn diffusion layer in the vicinity of the crack tip. Based on the model, they postulated that LME crack was caused not by liquid Zn, but by the presence of a thin α-Fe (Zn) layer at austenite grain boundaries formed by the Zn diffusion-mitigated phase transformation of the boundary region. The strength of this ferrite layer was low compared with the austenite, leading to the fracture during hot stamping. In the most recent work, Lee et al. [38] carried out tensile tests and three-point bending tests on the PHS after hot stamping. Results showed that the Zn coating has no cacoethic influence on tensile properties regardless tested in the length direction (LD) or transverse direction (TD) after hot stamping, but it deteriorated the bending performance of wall side significantly due to the LME cracking in the location. TD-oriented samples provided the worst bendability because the bending direction coincided with the microcracks propagation direction. Lee et al. [39, 40] also studied the effect of a 55 wt% Al–Zn coating on PHS during hot stamping and found the steel was not susceptible to LME, it was due to the fact that the liquid Zn was fully confined to the Al–Zn layer as intergranular islands or at the Fe–Al intermetallic grain boundaries, as the solubility of the Zn in the Fe–Al compounds was very low.

In the research by Drillet et al. [41], the cracks formed in the steel during hot forming were classified to macro-cracks (>100 μm) and micro-cracks. The macro-cracks were formed due to the liquid Zn penetration in the steel grain boundaries under stress, i.e. the LME. The cracks often located on the external side of the radius where the steel was under tensile stress. In this case, they claimed that the GI steel was only dedicated to indirect hot stamping process, but the GA steel could be dedicated to both direct and indirect hot stamping process with suitable heat treatment. The micro-cracks always initiated in the wall, where the friction between the steel sheet and the tools was very high. Kurz et al. [42, 43] also claimed that to avoid the LME during hot stamping, the indirect process was in industrial application for galvanized steels these days, however, it led to a much higher production cost. They introduced the so-called direct process with pre-cooling and the modified PHS, 20MnB8 and successfully avoided the LME cracking. Seok et al. [44] suggested that during the direct process, the heating time of 5 and 10 min with a heating temperature of 850 °C, heating times of 5 and 10 min with a heating temperature of 900 °C, and a heating time of 3 min with a heating temperature of 950 °C were appropriate for the product to minimize the LME cracks. Way to apply the direct hot forming process to galvanized steels and avoid the LME cracking can also be found in a patent [45].

5 LME of Galvanized Steels During Welding

The most dominant joining method in manufacturing industry is welding. During the welding process, the peak temperature in welding zone and heat affected zone (HAZ) is very high and far beyond the melting point of Zn. For the galvanized steel, Zn exists in liquid form and presents on the surface of solid steel in HAZ during fusion welding, thus there is a high risk of LME if the stress condition was up to grade in this area.

LME cracking is frequently observed in galvanized steels during resistance spot welding (RSW) [46–50]. Although some reports showed that the LME cracks have no significant influence on the tensile and fatigue properties of RSW joints [45, 51], but the surface crack is a potential threat to the performance and integrity of structures.

Kim et al. [52] detected surface LME cracks in RSW joints of the Zn-coated transformation-induced plasticity (TRIP) steel. The cracks mainly located in the concaves of welding centers and the inclined regions. It was found that welding force, welding current and welding time all had significant effect on surface cracking, it increased with the increase of welding current and welding time and the decrease of welding force. The holding time had less effect than other factors, the increase of holding time slightly decreased surface cracking. The electrode type also influenced the location and number of crack. By SEM observation and EDS analysis, they found that a Cu_5Zn_8 IMC, which formed by alloying with the Cu electrode, was present on the crack surface. An improvement method in this study was introduced, i.e. using a pre-current of 10 kA and 3 cycles to melt the Zn layer and a cooling time of 6 cycles to facilitate the removal of molten Zn before the application of welding current. Due to the lack of Zn, LME cracking was suppressed.

Barthelmie et al. [53] researched dissimilar RSW of the galvanized TWIP steel to the galvanized HX340LAD steel, they detected LME cracks on the TWIP steel side but not on the HX340LAD steel side, and they attributed it to the austenitic structures' sensitivity to LME. They also investigated the influence factors of the LME and found that the smaller heat input, the larger electrode force and electrode cap diameter could decrease the LME crack length.

Tolf et al. [54] found that the coating type and wear degree of the electrode cap had remarkable effect on LME cracking during RSW. The welds of GI coated dual phase (DP) steel were more prone to surface cracking compared with EG coated DP steel. With GI coating, cracks were observed when welding the first sample, and further increase in number and crack length with the ongoing of welding process. However, with EG coating, the first 50 welds were crack free. The authors claimed that the small amount of Al in hot dip galvanized coating was the key factor, as it was oxidized and forming aluminum oxide on the steel surface, and significantly increased the resistance during RSW. Higher resistance resulted in higher heat generation, and then higher LME cracking susceptibility.

Ashiri et al. [55] built up the concept of "supercritical area" and "critical nugget diameter" to describe the LME phenomena during RSW of Zn-coated TWIP steels. They found that most of the cracks were formed in the periphery area at the vicinity of the contacted area between the electrodes and TWIP steel sheets, as shown in Fig. 8. They defined the peripheral area as "supercritical LME area". SORPAS simulations confirmed that this area experienced highest temperature and stress, which gave an explanation that the conditions in this area was favorable for LME. In addition, the cooling condition in this area was worst because there was a gap between the electrode and this area. The authors further discovered that there was a lowest nugget diameter for LME to occur, which were 6.15 mm for GI coated steel, 6.21 mm for GA coated steels and 6.42 mm for EG coated steel, thus the EG coated steel had the lowest LME susceptibility. The maximum crack length increased with the increase of nugget diameter. They defined the lowest nugget diameter as "critical nugget diameter", which could be correlated with the critical tensile stress and temperature required for LME to occur. In another paper published by Ashiri et al. [56], the authors developed a smart welding procedure to produce LME-free welds of Zn-coated TWIP steel at high temperature. In their method as shown in Fig. 9, a two-pulse base current which was set to 5 kA provided the first step of heat input required to form minimum nugget diameter, then the second pulse current

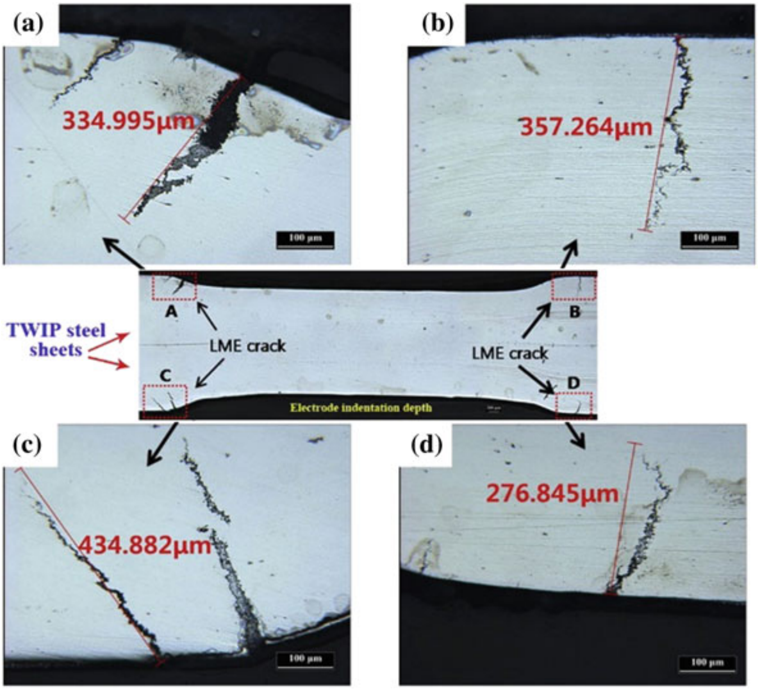


Fig. 8 Observation of LME in a resistance spot welded TWIP steel [55]

could be increased to the current where LME occurred. In the best welding schedule as shown in Fig. 9c, the weldable current rage without LME cracks was 85.7% greater than the current rage in single-pulse welding schedule. The LME cracking didn't occur until the expulsion, the expulsion was visible and easy to avoid, thus LME-free welds were obtained. SORPAS simulation results indicated that the temperature and stress concentration at the supercritical LME area of the impulse welded sample was much lower than that of the single-pulse welded one, which provided less liquid zinc and less tensile stress for LME to occur.

LME can also occur during arc welding. Bruscato [57] detected LME cracks when welded austenitic stainless steel to galvanized steel, and suggested that the zinc coating must be scrupulously removed from the joint area prior to welding to preclude LME cracking. Mori and Nishimoto [58] reported that LME intergranular cracking sometimes occurred in HAZ of dissimilar welded joints of austenitic stainless steels with galvanized carbon steels, the susceptibility of LME differed with various chromium and nickel contents which was due to the change in grain boundary energy in the austenitic steels. Pańcikiewicz et al. [59] also observed LME cracking in T-joints welded by Gas Metal Arc Welding (GMAW) between a hot dip galvanized E275D steel and a AISI 304 stainless steel. The cracks located in the HAZ of the stainless steel with length up to 3 mm, and had an intergranular character, Zn atoms presented on the crack surface. The zinc melted on the

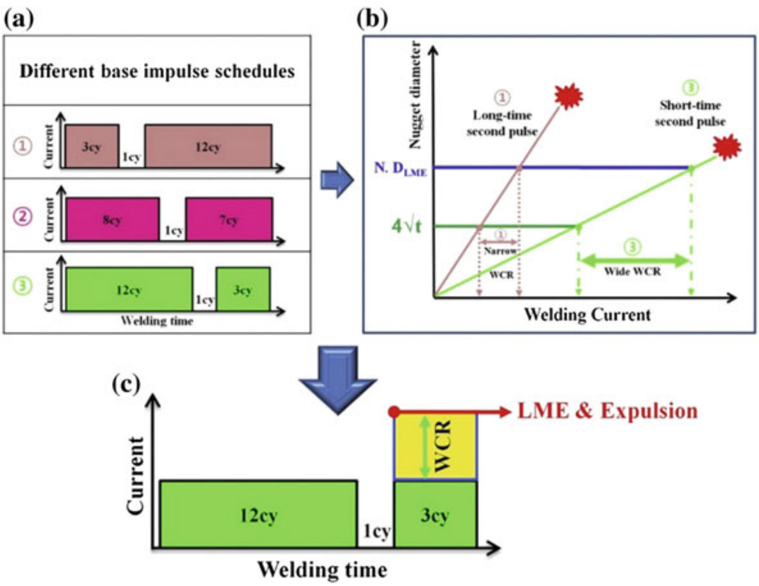
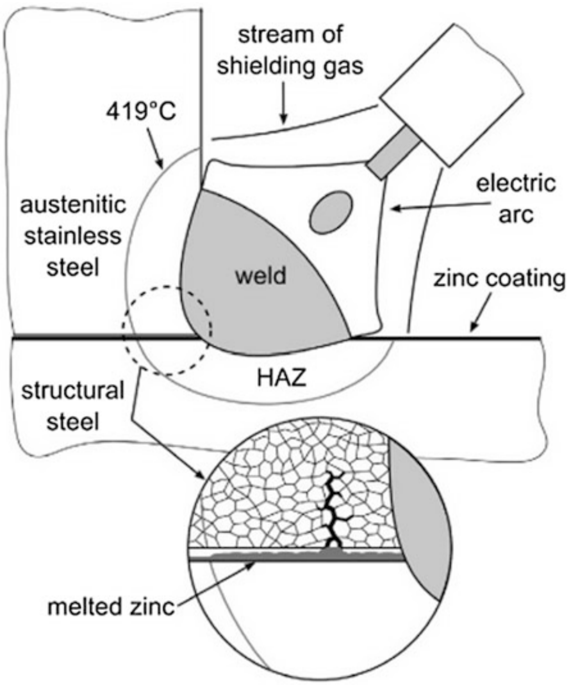


Fig. 9 **a** Different base impulse schedules; **b** the criterion for the selection and **c** conditions of the best welding schedule [56]

Fig. 10 A schema of the mechanism of zinc vaporizing and depositing on austenitic stainless steel during arc welding a T-joint with a fillet weld [59]



galvanized steel surface, then evaporated and condensed on the austenitic stainless steel by surface tension and adhesive forces. Liquid zinc slowly penetrated along grain boundaries, and the internal stress originated from phase transformation resulted in the fracture, as shown in Fig. 10.

6 Conclusion

Liquid zinc can embrittle various steels by LME mechanism. Many factors, such as temperature, strain rate, pre-exposure, cold deformation, coating types and constituents influence the severity of the embrittlement. The required conditions for LME may be reached during industrial processed such as hot-dip galvanizing, hot stamping and welding, the occurrence of LME cracking is an undesirable phenomenon and bring challenges to those industrial processes. Considering that the high temperature during the hot working industrial processes is inevitable, the stress condition should be carefully controlled to avoid the LME. Some attentions should be paid as follows:

1. High residual stress and stress concentration should not be reserved in the steelwork which is going to experience hot-dip galvanizing process, it can be achieved by rational design of large welded structures.
2. Try not to apply the galvanized steels to direct hot stamping process, and use the galvannealed steels to replace them.
3. The heat input during resistance spot welding of galvanized steels should be controlled by applying the novel welding procedure, electrogalvanized steels are good substitutes for hot-dip galvanized steels as they are able to reduce the risk of LME.

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