Analysis of Liquid Metal Brittleness in Ultra-high Strength Galvanized Sheet

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Abstract. The application ratio of ultra-high-strength galvanized steel sheets in automobiles is increasing year by year. Due to the low melting point of the galvanized layer, it be melted to liquid phase metal at the welding temperature. After contacting the solid material, the liquid phase metal be penetrated into the matrix along the grain boundary from surface to the matrix, leading to metal brittleness LME. It has been verified that the generation mechanism of LME is that after solid metal adsorbs the liquid metal, it promotes the emission, proliferation and movement of dislocations in solid metal, resulting in brittle cracking by the liquid metal, which reduces the impact toughness of the joint. LME can be controlled and prevented by means for methods of reducing the heat input of welding.

Keywords: Ultra-high strength steel Galvanized sheet · Liquid metal brittleness LME · Multi-pulse spot welding process

1 Foreword

In 2019, China's automobile production and sales reached 25.721 million and 25.769 million respectively, during the consecutive 12 years from 2005 to 2017, the average growth rate was 14.4%, and the car ownership reached ≥200 million. With the increase of car ownership, China has been caused double pressure by environment and external dependence on crude oil. In order to alleviate the pressure, the Ministry of industry and information technology of China have proposed and issued GB 27999–2019 "evaluation methods and indicators of fuel consumption of passenger cars", the standard stipulated that the average fuel consumption of passenger cars will be reduced to 4 L/100 km by 2025, and the corresponding CO_2 emission will be about 95 g/km, down 20% from the current 5 L/100 km.

One of the effective ways to reduce fuel consumption of vehicle is to achieve light weight of vehicles. The curb weight of the vehicle directly affects the rolling resistance, climbing resistance and acceleration resistance of the vehicle, thus increasing Carbon dioxide emission, as shown in Fig. 1. According to statistics, if the curb weight reduced 10%, the fuel consumption will be reduced by 8%, and carbon dioxide emission can be reduced by 4%.

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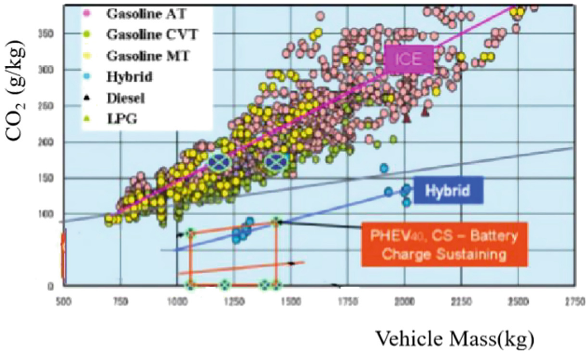


Fig. 1. Relationship between vehicle curb weight and CO_2 emission.

In order to improve lightweight and collision safety of vehicle, the main way is to increase the application proportion of ultra-high strength steel in BIW. At present, the application proportion of high strength steel is ≥65% in BIW, the ultra-high strength steel is ≥30%, and the application proportion of hot formed steel with strength ≥1500 MPa is ≥18%, which shows an increasing trend year by year.

2 Liquid Metal Brittleness LME Failure of Ultra-high Strength Galvanized Sheet When Welding

Ultra-high strength steel refers to the steel plate with yield strength greater than 550 MPa or tensile strength greater than 700 MPa. It is mostly used for collision safety parts of vehicle body, such as A and B pillar, rocker, bumper beam, front floor longitudinal beam, middle tunnel, etc. For the purpose of lightweight, most of these parts adopt high-strength and thin-walled design, which has high requirements for the surface quality of the steel plate, such as decarburization, rust, knock, scratch and other defects are strictly prohibited. In view of the above considerations, the using proportion of coated steel sheet in the structure of car body shows an upward trend, such as the application of aluminum silicon coating or galvanized steel plate.

2.1 Spot Welding Process Parameters

Generally, the melting point of coating metal is very low. For example, the melting point of Zn is 420 °C, and the melting point of aluminum silicon coating is 650 °C. During spot welding of steel plate, under the action of welding current, the temperature of steel sheet in welding spot instantly rises to 700–900 °C, as shown in Fig. 2. The welding temperature is about 300 °C higher than the melting point of Zn layer. During welding, the Zn layer under electrode cap and around the welding spot is in liquid state. Under the action of welding pressure, the region around welding electrode cap is in a high tensile stress state.

During welding, the liquid metal rapidly infiltrates into the matrix through the grain boundary on the surface of the welding base metal, and forms liquid-phase brittle crack

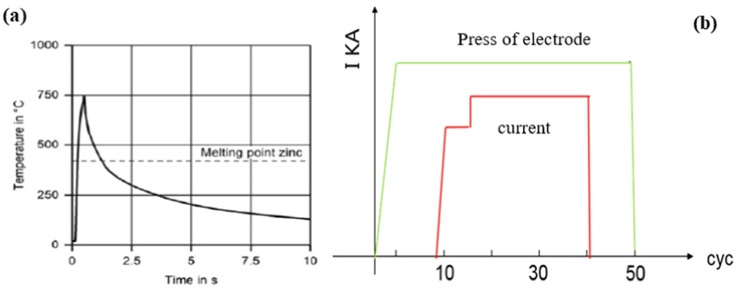


Fig. 2. Spot welding process parameters and thermal cycle curve of spot welding; (a) Temperature thermal cycle of spot welding;(b) schematic diagram of spot-welding process parameters.

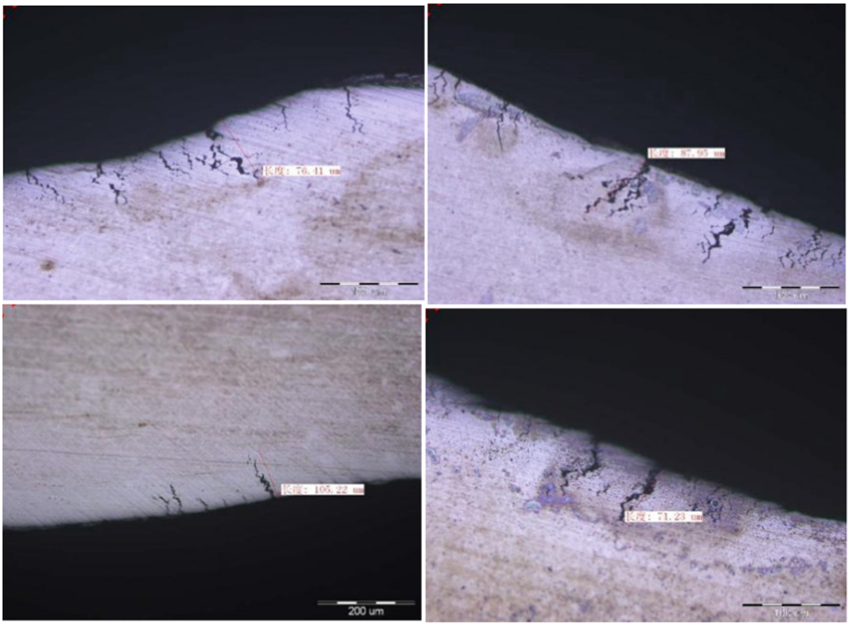
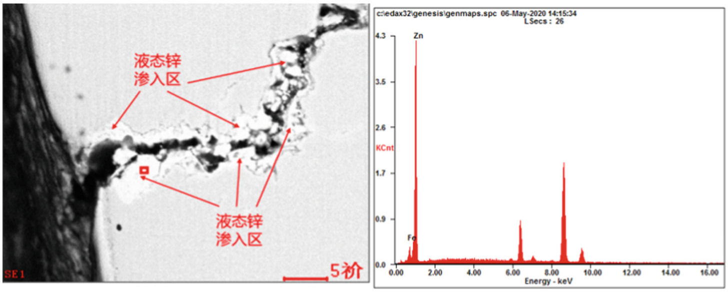


Fig. 3. Surface crack around nugget for 980 MPa GI steel sheet.

LME along with the increasing of tensile stress in weld area. See Fig. 3 for details. Generally, the crack depth is 20 µm–200 µm, up to 900 µm. SEM and EDS analysis results See Fig. 4 for LME crack area. It is found that the liquid metal Zn is distributed through the two walls of the crack, and the permeability is very strong, which continues to deepen with the expansion of the crack.

2.2 The Effect of LME for Mechanical Properties of Spot

After spot weld create LME, the brittleness be increased, the toughness decreased, and the ability to resist impact fracture failure be decreased significantly. In order to test the effect of LME on the mechanical properties of spot joints, two cap beam structures



Element	Wt%	At%
FeL	14.58	16.65
ZnL	85.42	83.35
Matrix	Correction	ZAF

Fig. 4. EDS analysis results of LME crack.

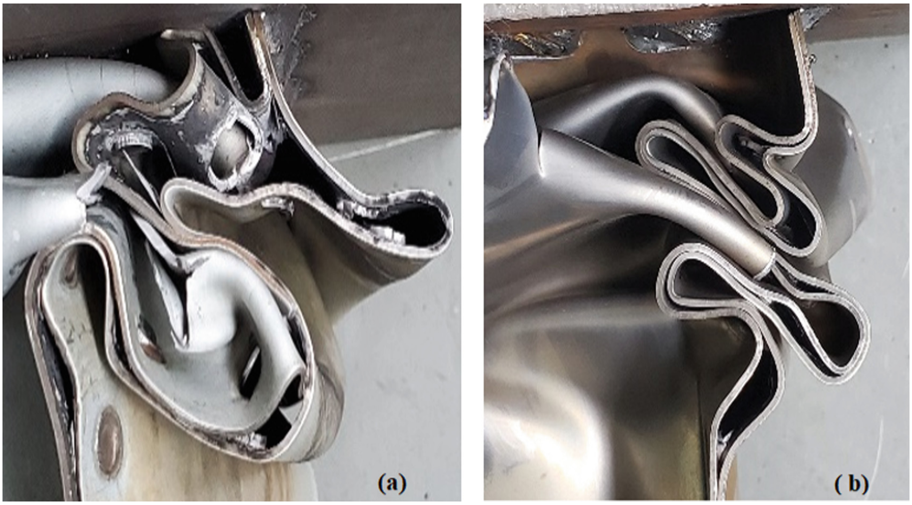


Fig. 5. Comparison test results for effect of LME to impact performance of the spot, (a) failure mode of LME spot weld; (b) failure mode of no LME spot weld.

using cold rolling bare sheet or galvanized sheet with 980 MPa were made respectively for collision comparison test. The collision speed is 62.3 km/h and the loading mass is 516 kg. See Fig. 5 for the results of collision comparison test.

It can be seen that under the same impact load, the fracture failure rate of LME's spot weld is higher than spot without LME from Fig. 5, indicating that the liquid phase metal brittle LME seriously reduces the toughness of spot weld, reduces the crushing energy absorption and increases the fracture failure risk ratio of spot weld.

3 Analysis of Causes for Liquid Metal Brittleness LME

As mentioned above, the necessary conditions to create LME are:

(a) The surface of the failed part contains low melting point metal or alloy coating.
(b) The working environment and processing temperature of material are significantly higher than the melting point of low melting point metal, such as welding and hot forming process, resulting in molten liquid metal creating during material be use and process.
(c) Due to the effect of the structure or service state of parts, the surface in failed parts certain a residual tensile stress.

After the necessary conditions for forming LME are met, the low melting point metal penetrates into the material along the grain boundary of the part's surface, cause the embrittlement of the metal material and lead to the failure of the part. It is called low melting point metal contact embrittlement crack, which referred to as metal erosion embrittlement crack or thermal pollution crack of low melting point metal. The main manifestation of the failure of parts to cause by liquid metal is the brittle cracking caused by liquid metal. This brittle fracture often occurs in an instant, and the consequences are also very serious.

Zhou of Beijing University of science and technology and other researchers have proved that solid metals adsorbed by liquid metals can promote the emission, proliferation and movement of dislocations. When the emission and movement of dislocations reach the critical state, the brittle microcracks nucleate and cleavage extension at the top of the original crack or in the dislocation free region [1]. According to Griffith formula [2], which characterizes cleavage fracture,

Cleavage fracture stress can be expressed as in Eq. (1).

$$\sigma_{\mathrm{fra}ct} = \sqrt{\frac{2E_{\gamma_{\alpha}}}{\pi(1-\nu^2)\alpha}} \tag{1}$$

where, γ_a-Surface energy of cracked particles, α-Critical crack length, ν-Poisson's ratio of material, E-young's modulus of elasticity.

When solid metal surface be directly touch by a liquid metal, it often makes the metal wet and brittle, and cracking from the surface under the action of tensile stress. After the low melting point liquid metal atoms are adsorbed at the crack tip, it furtherly reduces the crystal bond strength of solid metals, leads to brittle crack propagation. The contact embrittlement failure of low melting point metal will not occur without combined action of tensile stress and certain temperature, the tensile stress can be external tensile stress or residual stress formed in processing parts [3].

The LME sensitivity is also related to the chemical composition and strength of the base material, which is directly proportional to the carbon equivalent and tensile strength as well as the silicon content of the base material. When the tensile strength of the base material is greater than 800 MPa, the silicon content in the chemical composition is greater than 1.2%, the risk of LME is high after high-temperature processing. Liquid phase metal brittleness is related to the composition of the coating, and the LME risk of GI coating is greater than that of GA and EGI coating.

4 Methods to Prevent Welding LME for High Strength Galvanized Steel Sheet

As mentioned above, the liquid phase metal brittleness LME is related to the welding heat input and the surface tensile stress state. When formulating the welding process parameters, it should be considered to shorten the high-temperature residence and welding time of the welding as far as possible, and using the arc electrode cap to avoid too small the electrode indentation and leading to increase the strain stress. During to design the welding process, the following measures shall be taken to prevent the generation of welding LME.

(1) The electrode cap of the welding machine shall be repaired in time. After repair, the transition area of the contact plane between the electrode cap and the sheet shall maintain arc transition.
(2) To enhance cooling speed of the electrode and reduce the decrements of heat dissipation rate caused by electrode heating.
(3) To correct the electrode position before welding. The dislocation of upper and lower electrodes shall be ≤ 2 mm and the angle deviation shall be $\leq 3°$;
(4) Increasing electrode pressure can effectively reduce LME.
(5) The plastic deformation area at the edge of the weld indentation is the area with the maximum tensile stress and the area with high incidence of LME cracks. In order to reduce heat input and thermal deformation, the width of welding pulse should be reduced.
(6) Welding parameter optimization - multi pulse welding process is adopted. It is recommended to use the process route of the three current pulse as showing in Fig. 6, which can effectively avoid LME. The front current pulse can remove the zinc (Zn) layer on the surface of the spot weld to reduce the amount of liquid zinc metal during heating. The current value of the front pulse shall be less than that of the main welding pulse, and the width of pulse shall be twice that of the rectangular wave of the main welding pulse.
(7) In order to prevent a large heat input at one time, the cooling time of one cycle is added between three heating pulses, which can effectively reduce the residence time of welding metal in high temperature area, to reduce spatter and overcome LME.
(8) To extend the pressure holding time after welding, increasing the cooling speed of weld, to make the surface temperature of spot joint lower than the melting point of Zn element when the upper and lower electrodes are disconnected, and reduce the infiltration of liquid metal.
(9) Post current pulse can reduce the residual stress of weld to improve the strength of weld.

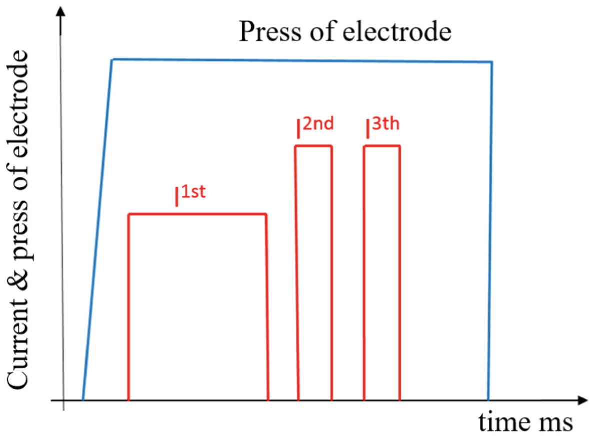


Fig. 6. Recommended process for avoiding spot LME.

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