DETERMINATION OF LIQUID METAL EMBRITTLEMENT AFTER RESISTANCE SPOT WELDING OF ZN-COATED HIGH-STRENGTH STEELS

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Abstract

The weight reduction of vehicle body and parts become much more crucial to decrease CO_2 emissions. The use of high-strength steels has increased within the scope of vehicle weight reduction studies. The corrosion resistance must be also ensured for automotive structural components. Therefore, zinc-coated high strength steels have been developed. Liquid metal embrittlement (LME) occurs during resistance spot welding (RSW) on zinc-coated high strength steels The liquid zinc from the coating penetrates along the grain boundaries in the material, where it leads to surface cracking. In this study, LME formation was investigated on zinc coated high strength steels during resistance spot welding (RSW). The effect of different type of zinc coating on LME formation was also considered. The results show that the type of zinc coating as well as the grade of the steel have considerable effect on LME formation. The maximum LME crack length was measured as 387 μm on GI coated Q&P 1180- Q&P 1180 welded joints by RSW.

Keywords: Advanced high strength steels, galvanized coating, resistance spot welding, liquid metal embrittlement

1. INTRODUCTION

Light weight body structure design using of advanced high strength steels (AHSS) plays an important role for improving fuel economy and reducing harmful CO_2 in the automotive industry [1]. Recently, AHSS group among advanced materials group gain considerably attention [2]. Due to the expectation of improved corrosion resistance in AHSS, the application of galvanized coated steel has significantly increased [3]. A thin layer of zinc element is applied on to steel for corrosion protection by galvanization. Hot dip galvanised coating (GI) is mostly carried out due to the ease of apply and low cost issues. In literature it has been recently reported that the Zn coated AHSS are rather susceptible for liquid metal embrittlement (LME) cracking during resistance spot welding (RSW) [4,5]. The molten zinc (Zn) atoms from the galvanised coted layer diffuses through the grain boundaries into the base material, where it causes LME crack occurance [6]. Cracks and brittle fractures occur during solidification. It is widely known that LME occurance depends on due to various reasons such as liquid Zn, welding parameters, alloy strength as well as thermal history and galvanised coating type [5-8]. It was observed that steels with tensile strengths higher than 1000 MPa exhibit the highest LME crack sensitivity [8]. In addition, the type of Zn based coating also play an important role on the LME crack sensitivity. GI has the most trigger effect for the LME crack formation according to literature [9-12]. Several studies have been conducted to determine the effect of welding parameters on the severity of LME. The results show that a greater heat input corresponds to more severe LME accurance [10,13,14]. LME occurance appear on the surface of RSW. At the very beginning of the welding, the temperature is low. The base metal and coating are preserved in their original condition. Compression force is applied to the center of the capillary effect with the electrode. As the welding time progresses, the welding temperature rises. The base material turns into austenite phase structure and the coating melts at high temperature. The coating in the center of the capillary effect reacts with the electrode and the liquid phase is ejected under the force of the electrode, resulting in a significant loss of Zn. Due to the presence of a tensile stress caused by mechanical or thermal stresses, Zn atoms diffuse into the steel along the austenite grain boundaries because the diffusion rate is very fast [15]. As a result, diffused Zn causes weakening nearby the grain boundaries. The crack initiation can be start at weaker grain boundaries under tensile stress and LME cracks may occur.

In this study, RSW was applied on 3 different welded joints combined with AHSS steels with a different galvanised coating type in order to determine the LME sensitivity. LME occurance by different RSW parameters and the weld zone of the welded joint were characterized by magnetic particle test, optical microscope (OM) and scanning electron microscopy (SEM).

2. EXPERIMENTAL PROCEDURES

In this study, hot-dip galvanized coated (GI) Q&P 1180, electro galvanized (EG) coated TBF 980 and uncoated (UC) TBF 980 steels were used. The nominal sheet thicknesses of TBF 980 UC, TBF 980 EG and Q&P 1180 GI are 1.2 mm, 1.2 mm and 1.5 mm, respectively. The steel plates were prepared by laser cutting in 30x100 mm dimension and surface of the steel plates were cleaned by ethanol before RSW. The welding operation (200 kVA) was carried out in RSW machine operating with alternative current (AC) at a frequency of 50 Hz by copper electrodes in 6.0 mm diameter. The RSW was performed when the steel plates overlapped as 30 mm. The welding parameters is shown in **Table 1**.

Table 1 Welding parameters used in the study

Parameter no	Welding current (kA)	Electrode Force (daN)	Number of pulses	Welding time (ms)	Hold time (ms)
P1	8.5	250	2	200	300
P2	9.2	300	1	300	300
P3	8	300	3	500	300

Magnetic particle test was performed to determine LME cracks before metallographic specimen preparation. The welded joints were cut out from the nugget center by METKON METACUT 302 metallographic sensitive cutting equipment. Cross section of welded specimens was mold by METKON ECOPRESS 52 hot molding machine. The standard metallographic grinding and polishing were performed by METKON FORCIPOL 202 unit. Cross section of welded specimens was investigated by Nikon SMZ745T optical microscope. LME cracks were detected and the crack lengths were measured. The identified LME cracks were examined in details by CARL ZEISS ULTRA PLUS GEMINI FESEM model scanning electron microscope (SEM) and elemental analysis (EDS) was performed on the LME cracks in order to prove the presence of zinc (Zn) element.

3. RESULTS AND DISCUSSIONS

3.1. Magnetic particle tests

It is important to detect LME cracks before macro/micro structural investigations. Otherwise, the obtained data may be inaccurate and misleading. Non-destructive testing methods such as liquid penetration testing, X-ray testing can be used to detect deep cracks on the surface of spot welds. In this study, the fluorescent magnetic particle test method was used to detect cracks on the surface of spot welds before metallographic specimen preparation. Magnetic particle test was applied to the welded joints obtained with three different parameters. The density and locations of LME cracks on the spot surface were determined. **Figure 1** shows magnetic particle test result images. In **Figure 1**, the LME cracks are clearly seen on both front and back surface of the nugget. The amount and length of LME cracks are affected by the parameter changes, welded joint material and coating type during welding.

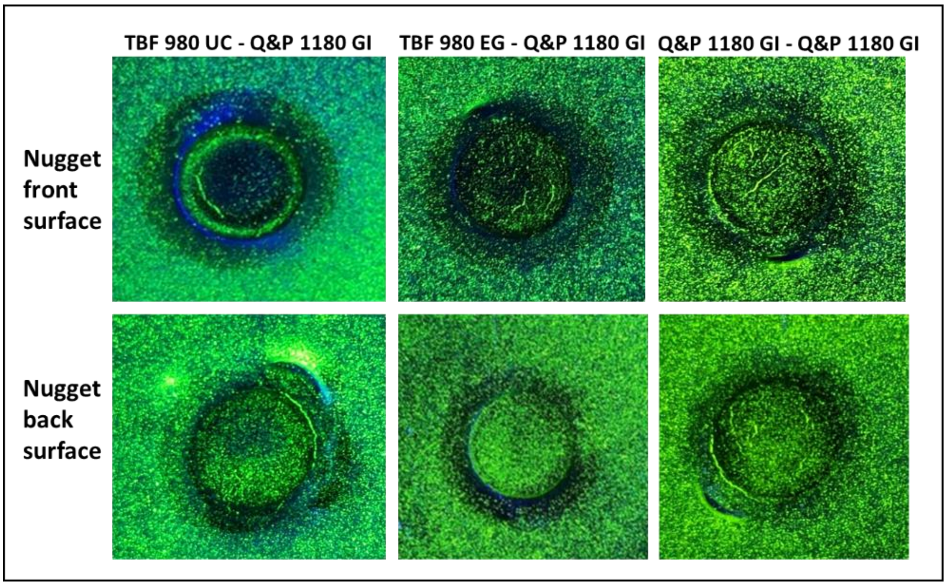


Figure 1 Magnetic particle test results

3.2. LME macro / micro structural investigations

Macro images of welded joined with a different RSW parameters were shown in **Figure 2**. The LME crack depths were calculated by measuring the detected crack lengths. The maximum measured LME crack depths for each welded joints with a different RSW parameters were also illustrated in **Table 1** for a comparison. It has been reported that the amount of cracks in both weld metal and HAZ were affected by the parameter changes during RSW AC current. The sensitivity of LME crack formation is quite evident with these parameters [4]. According to **Table 1**, the influence of the Zn coating type on LME crack occurance can be distinguished. In literature, all studies underline that hot dip galvanised (GI) Zn-coated steels has higher LME occurancy compared to steels coated with hot dip galvannealed (GA) or electro-galvanised (Zn–Ni) coatings [9-11]. LME occurancy depends on the melting point of the coating type. The lower melting point of GI (Zn) coating compared to GA (Fe–Zn) and EG (Zn–Ni) coatings could have more liquid fraction of Zn for LME crack formation. Intermetallic compound formed between the solid metal and liquid metal during EG and GA Zn coating [7]. GA and GE coatings contain Fe-Zn and Zn-Ni intermetallic compounds, respectively. This may be the explanation of the reduction the risk of LME formation in GE and GA Zn coating. The maximum LME crack length was measured as 387 μm in Q&P 1180 GI - Q&P 1180 GI welded joint. As the strength of steel increased, the susceptibility of LME formation increased.

Table 2 The maximum measured LME crack depths for each welded joints with a different RSW parameters

Welded joints	Welding parameter	LME crack length [μm]
TBF 980 UC - Q&P 1180 GI	1	63.77
	2	104.23
	3	157.43
TBF 980 EG - Q&P 1180 GI	1	98.23
	2	73.5
	3	52.83
Q&P 1180 GI - Q&P 1180 GI	1	369.03
	2	387.12
	3	121.05

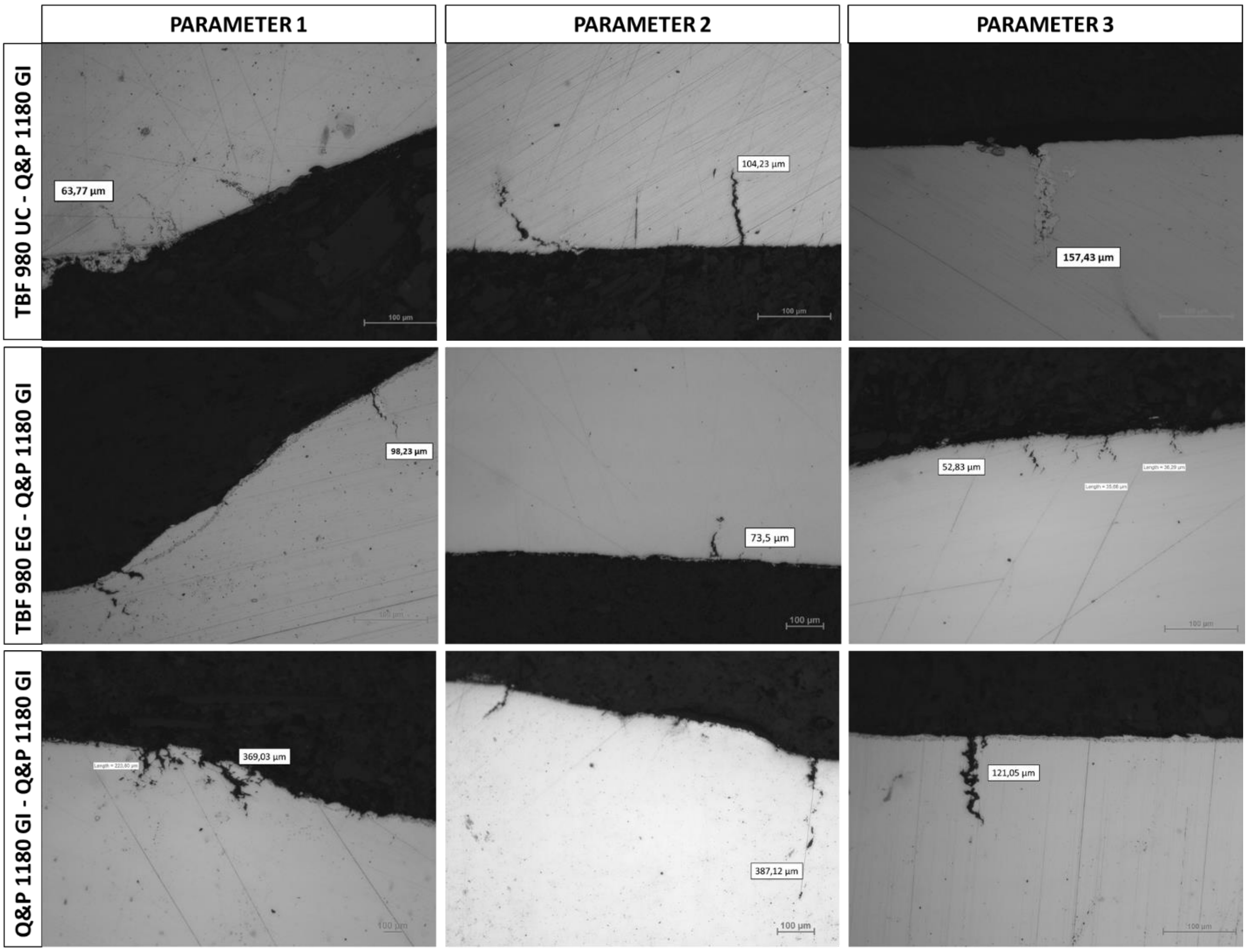


Figure 2 LME crack images and crack lengths on welded joints with a different welding parameters

In order to analyse LME cracks in details, SEM was performed on the LME crack areas of welded joints and micro images were illustrated in **Figure 3**. SEM images were taken on the maximum measured LME crack depths for each welded joints at different welding parameters according to **Table 1**. Minor cracks were also observed well ahead of the LME crack tips (**Figure 3**). The LME crack can propagate along these predamaged zones and coalesces with the cavities. This leads to a more pronounced increase of the LME crack length under loading conditions [16]. Therefore, mechanical properties of welded joints containing LME cracks should be considered.

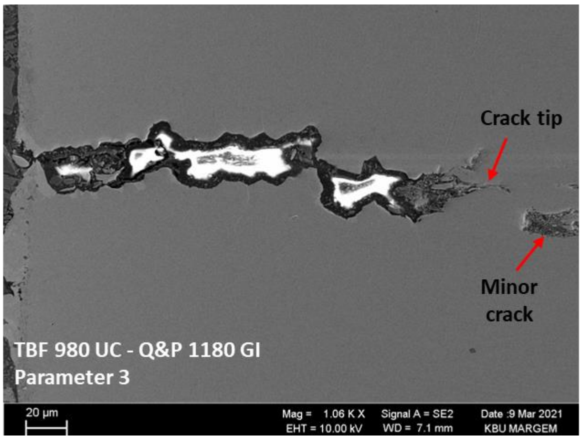


Figure 3/1 SEM micro images on LME crack areas of welded joints

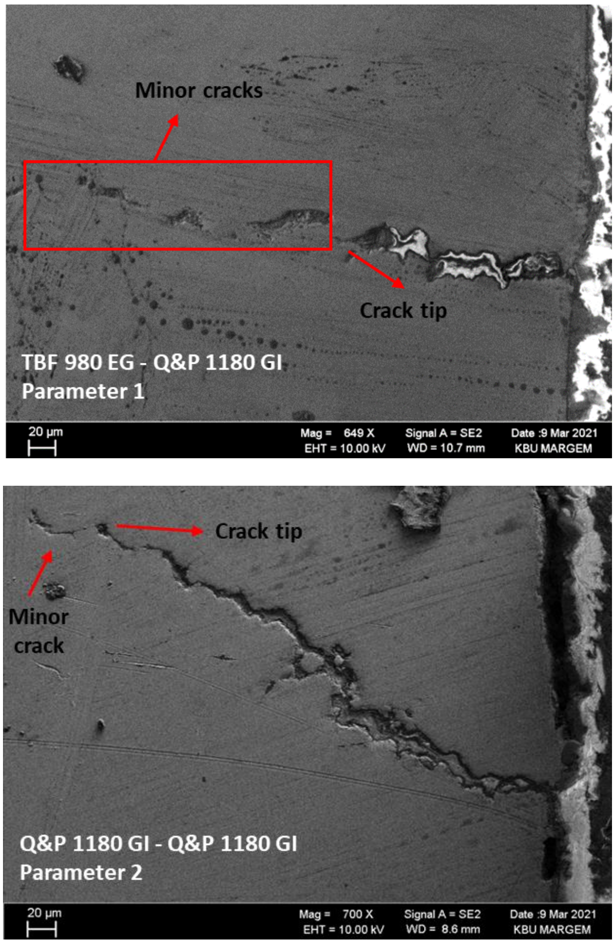
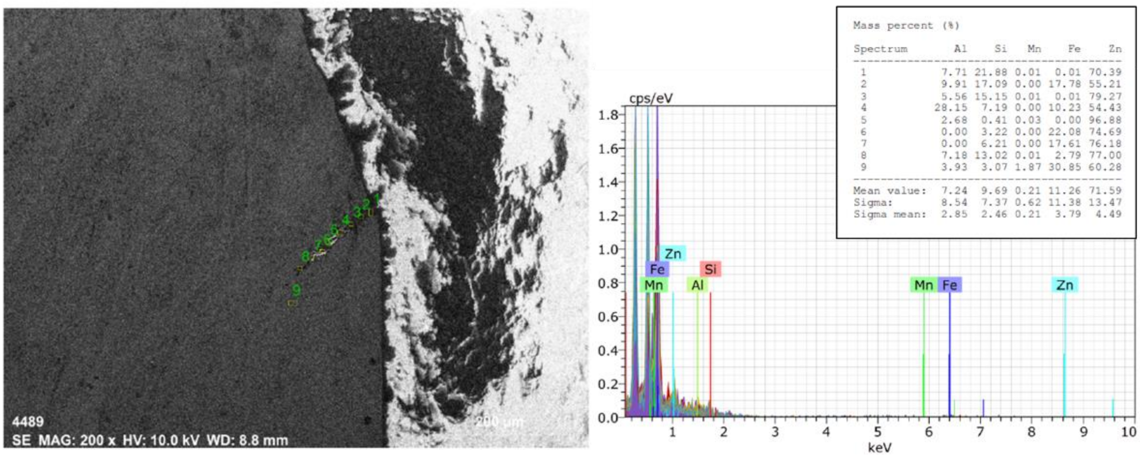


Figure 3/2 SEM micro images on LME crack areas of welded joints

The observed LME cracks were detected with a SEM- EDS (Energy Dispersive X-ray Spectroscopy) detector from the crack surface to the weld nugget. **Figure 4** shows the regional elemental analyzes performed at random intervals from the beginning to the end of the LME cracks. Higher mass percent of Zn element (in between 37% and 70%) was detected along of the LME cracks. This result is evident that the cracks are pronounced as "LME cracks" as a result of Zn penetration from the galvanised coating in to the base material during RSW.



Mass percent (%)

Spectrum	Al	Si	Mn	Fe	Zn
1	7.71	21.88	0.01	0.01	70.39
2	9.91	17.09	0.00	17.78	55.21
3	5.56	15.15	0.01	0.01	79.27
4	28.15	7.19	0.00	10.23	54.43
5	2.68	0.41	0.03	0.00	96.88
6	0.00	3.22	0.00	22.08	74.69
7	0.00	6.21	0.00	17.61	76.18
8	7.18	13.02	0.01	2.79	77.00
9	3.93	3.07	1.87	30.85	60.28
Mean value:	7.24	9.69	0.21	11.26	71.59
Sigma:	8.54	7.37	0.62	11.38	13.47
Sigma mean:	2.85	2.46	0.21	3.79	4.49

Figure 4/1 SEM-EDS elemental analysis of the LME cracks detected on the welded joints

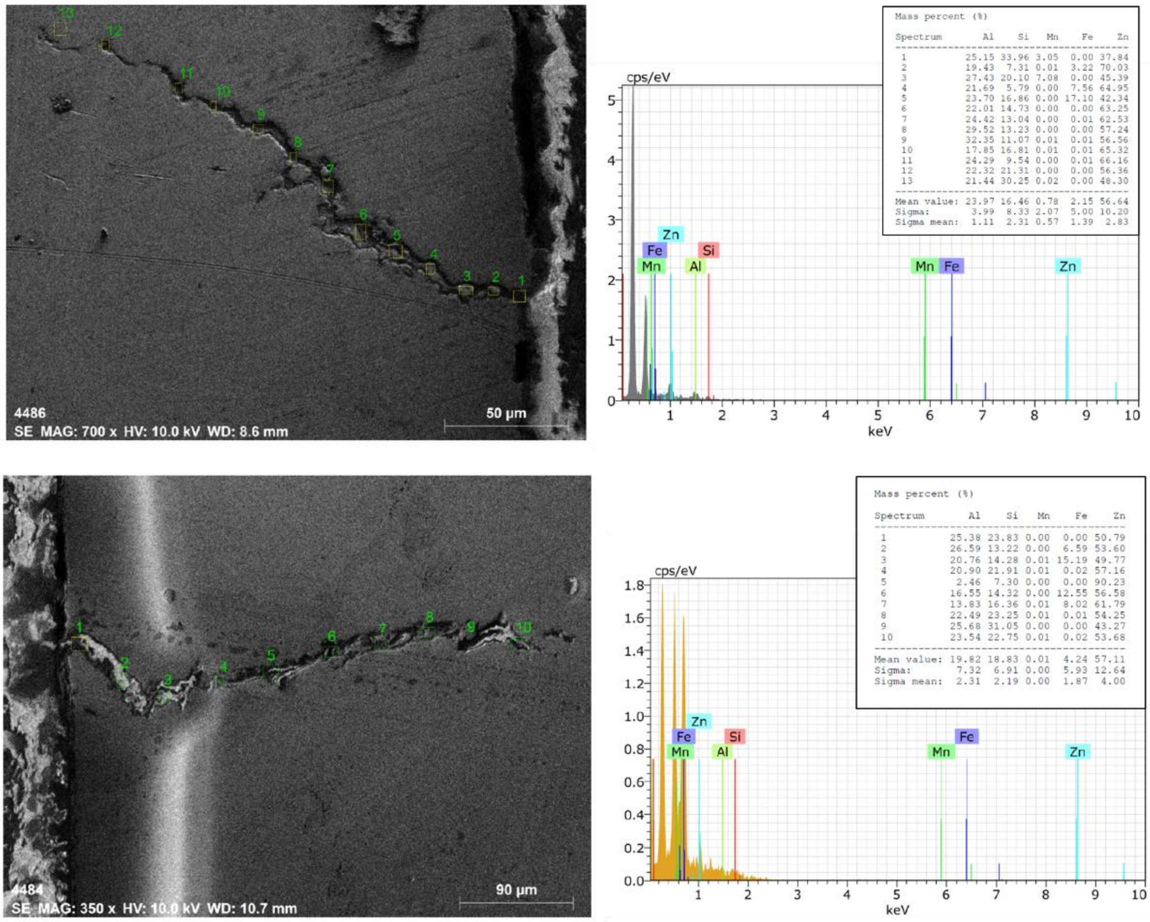


Figure 4/2 SEM-EDS elemental analysis of the LME cracks detected on the welded joints

4. CONCLUSIONS

In this study, RSW was applied on 3 different welded joints combined with AHSS steels with a different galvanised coating type in order to determine LME sensitivity. The test results are summarized as follows:

- LME cracks on the surface of the spot welds were determined by magnetic particle test, optical and electron microscopy imaging methods.
- The maximum LME crack length was measured as 387 µm in Q&P 1180 GI - Q&P 1180 GI welded joint. As the strength of steel increased, the susceptibility of LME formation increased.
- Minor cracks were aobserved well ahead of the LME crack tips. The LME crack can propagate along these predamaged zones and coalesces with the cavities. This leads to a more pronounced increase of the LME crack length under loading conditions. Therefore, mechanical properties of welded joints containing LME cracks should be considered.
- The observed LME cracks were detected with a SEM- EDS detector from the crack surface to the weld nugget. Higher mass percent of Zn element (in between 37 % and 70 %) was detected along of the LME cracks proofs that the cracks are pronounced as “LME cracks” as a result of zinc penetration from the galvanised coating in to the base material during RSW.

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