Status of Analysis and Countermeasures

Liquid Metal Embrittlement

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ABSTRACT

During spot welding, some zinc coated Advanced High-strength steels (AHSS) are prone to suffer from Liquid Metal Embrittlement (LME). The zinc present at the surface of the steel melts due to its low melting point (420 °C). Under certain conditions (temperature, stress, time, etc.), a rapid penetration of the liquid zinc along the grain boundaries may cause embrittlement. Cracks are then observed at different locations of the spot welds. Avoiding LME or, at least, quantifying its impact on the behavior of the assembly becomes one of the main objectives of steel manufacturers and carmakers.

LME cracking depends on the material and the welding conditions. One material which could be considered as sensitive to LME in certain conditions could also be considered as non-sensitive in other conditions. Furthermore, LME is a scattered phenomenon, the presence, occurrence and size of the cracks could vary from one spot weld to another. The current paper gives an overview of analysis and countermeasures particularly on:

- Some testing conditions during welding processes that produce LME cracks with increasing severity of certain parameters (such as welding current, gap between sheets, misalignment, electrodes shape/diameter).
- Mitigation of cracking sensitivity by the type of stack-up (2 and 3 sheets in homogeneous and heterogeneous configurations) and thus allowing access to certain part designs where the most severe configurations can be ruled out.
- Effect of such cracks on the mechanical performances of spot-welds. When these cracks occur on the surface of the spot-welds, they are not on a transfer path of force and therefore do not show a decrease in performance during static, dynamic and fatigue loading.

INTRODUCTION

In this paper, the LME sensitivity of a Fortiform®1180 CFB (Carbide Free Bainite) EG steel will first be discussed through the influence of the different combinations of two and three sheets connections with other steels, but also through the influence of its thickness for the most severe combination. This grade is known to have a high LME sensitivity which allows to differentiate welding stacks-up conditions regarding LME crack occurrence.

This grade is not more available in ArcellorMittal Europe, the current development is based on a Quenching & Partitioning (Q&P) Hot Dip Galvanised (GI) version. Following this, the effect of aggravating factors on sensitive configurations such as misalignment of the electrodes (lateral or angular) or the clearance between the welding electrode and the sheet will be discussed. Additionally, the welding parameters that could reduce crack sizes, such as electrode diameters & shape or welding currents, will be discussed.

It will also be shown that if the crack sizes are controlled, the impact on mechanical strength in quasi-static, fatigue or crash is negligible.

Finally, we will show by means of the metallurgical design improvements that our latest product development can result in reduction in LME behavior of our Fortiform® steels.

STACK-UP INFLUENCE ON LME

Fortiform 1180 CFB EG was welded in two and three sheet homogeneous and heterogeneous configurations. Different steel grades (Fortiform 1180 EG, CR3, Usibor 1500 AS 150, DP 980 GI) and thicknesses were used as accompanying sheets.

For each stack-up, ten spot welds were made on plates of 50 × 300 mm at the maximum current level (200A under splashing limit). The welding parameters are given by the ISO 18278-2 standard, whatever the stack up:

- Welding machine: 50 Hz pedestal
- Electrode: F1-16-6 mm
- Welding force, welding time and holding time according to ISO 18278-2 are determined by:
  - the thinner sheet when welding two sheets of unequal thickness,
  - the thinner of the two thicker sheets when welding three sheets stack-up,
  - the highest Ultimate Tensile Strength (UTS) when sheets with differing UTS are welded together.

All spot welds were first evaluated by dye penetrant and then by cross-section observations. Stack-ups were ranked based on the maximum crack depth in each spot weld (Figures 1.a et 1.b).

Fortiform®1180 shows very low LME sensitivity when welded in homogeneous or in heterogeneous configurations with other conventional AHSS (Dual Phase or Press Hardened Steel Usibor).
Only small cracks (<100 µm) were observed for almost all of these configurations. However, deeper cracks were observed when the Fortiform 1180 was welded with Mild or HSLA steel grades.

To study the impact of the sheet thickness on LME, it was necessary to use a substrate of same chemistry and microstructure. Thus, a 2.0 mm Fortiform®1180 steel sheet was progressively grinded to 1.8, 1.6, 1.4, 1.2, 1.0 and 0.8 mm, electrogalvanized and then welded in a very severe three sheet heterogeneous configuration (Fortiform®1180 / Mild Steel / Mild Steel) for LME evaluation (Figure.2).

LME cracks deeper than 200µm were observed for almost all the thicknesses, except for 2.0 mm. This could be explained by the fact that sheets of 1.8 and 2.0 mm produced smaller nuggets than those having thicknesses varying

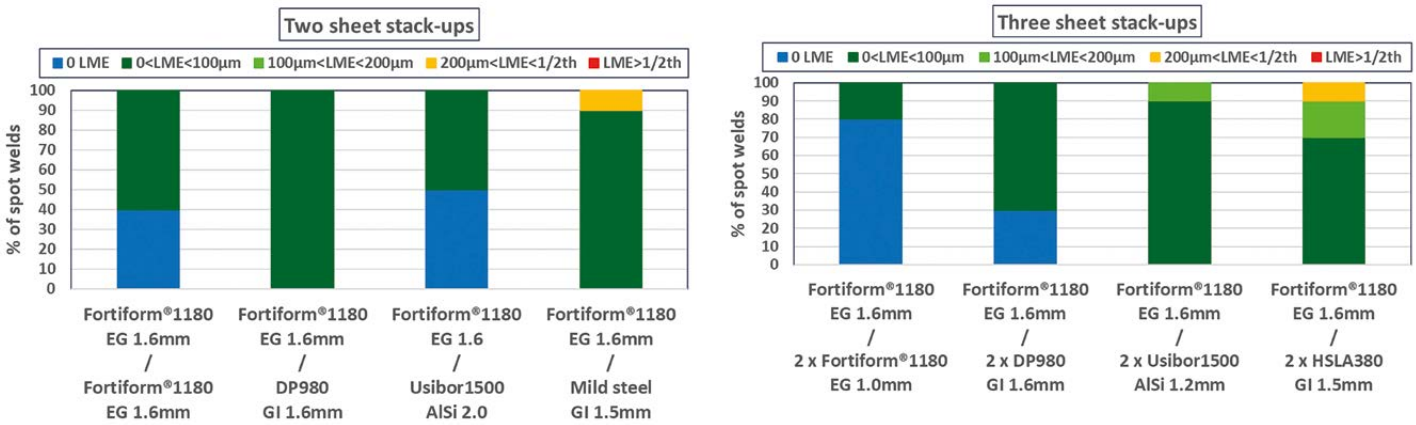

Figure 1.a and figure 1.b show LME sensitivity levels of Fortiform 1180 1.6mm welded in two and three sheet stack-ups respectively

between 0.8 and 1.6 mm. These results revealed that the sheet thickness has no significant impact on the LME sensitivity level of Fortiform 1180 grade.

NOISE FACTORS TO REPRESENT INDUSTRIAL WELDING CONDITIONS

The objective of this section is to show the influence of industrial welding conditions on LME occurrence. These conditions were simulated by aggravating laboratory process parameters. These may certainly worsen the appearance of LME by increasing the local stresses during welding, but there is a need to provide recommendations in terms of limits not to be exceeded for each of these so-called noise factors. Indeed, these disturbance factors are sometimes used by some carmakers in their LME evaluation protocol. To quantify the impact, a medium sensitive configuration combining a 1.5 mm Fortiform®1180 EG with a 0.8 mm Drawing Quality has been used.

Figure 3 shows the impact of lateral misalignment of the welding electrodes on the occurrence of LME cracks. The results clearly show that a 1,5 mm distance between electrodes should not be exceeded to not considerably increase the crack sizes.

Figure 4 shows the impact of an angular misalignment on the appearance of LME cracks, and it is recommended to not exceed an angle of 5 ° which will considerably increase considerably crack size. Finally, the influence of the clearance between the sheet and the electrode on LME is evaluated, and must not exceed a thickness corresponding to the accompanying sheet of thinner thickness, here 0.8 mm (Figure 5). A very large clearance between the sheets (>3 mm) tends to reverse the local stresses and close the cracks.

SOME WELDING PROCESS MODIFICATIONS TO PREVENT LME

LME cracks in spot welding mainly appear at the top of the weldability range, i.e. for the highest welding current, close to expulsion. This is mainly explained by a higher heat input and higher stresses linked to the indentation caused by the electrodes. In this paragraph, we will illustrate two most promising process parameters for reducing crack sizes on several sensitive configurations, notably combining mild steels. Indeed, these mild steels require the use of higher welding currents due to their lower electrical resistivity (leaner chemistry than AHSS).

The two levers to reduce the size of the LME cracks that we present here are:

- Reducing welding intensities and consequently the size of the welds, while remaining above the minimum required size
- Modifying the electrode shape to minimize LME cracks. [1]

On figure 6, we show LME cracks sizes of two configurations with three sheets stack-up when they are welded at the maximum current (Imax) level. These cracks can be considerably reduced by a limitation of welding current (<10%). The weld diameters are certainly slightly reduced as well but remain perfectly acceptable (<10%) and far above the minimum weld size for such combinations.

Thomas Dupuy [1] proposed a novel electrode tip geometry to mitigate Liquid Metal Embrittlement during resistance spot welding. The reference electrode tip geometry has been chosen to be the standard F1-20-8 [6]. Another reference electrode has been considered, F1-20-10, which is supposed to be better for LME according to literature studies. Beside these references, the novel tip geometry is characterized by a central protrusion and an external sloping shoulder [7].

Figure 7 displays all these geometries, together with their main dimensions. All electrodes were made of Cu-Cr-Zr alloy.

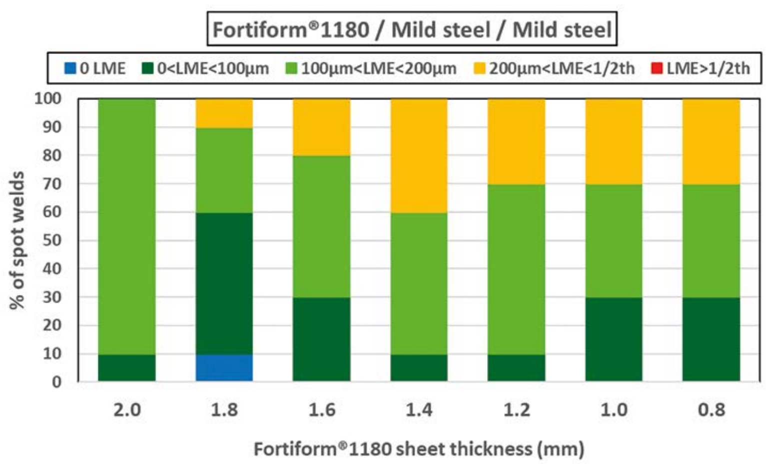

Figure 2. Impact of the thickness on LME.

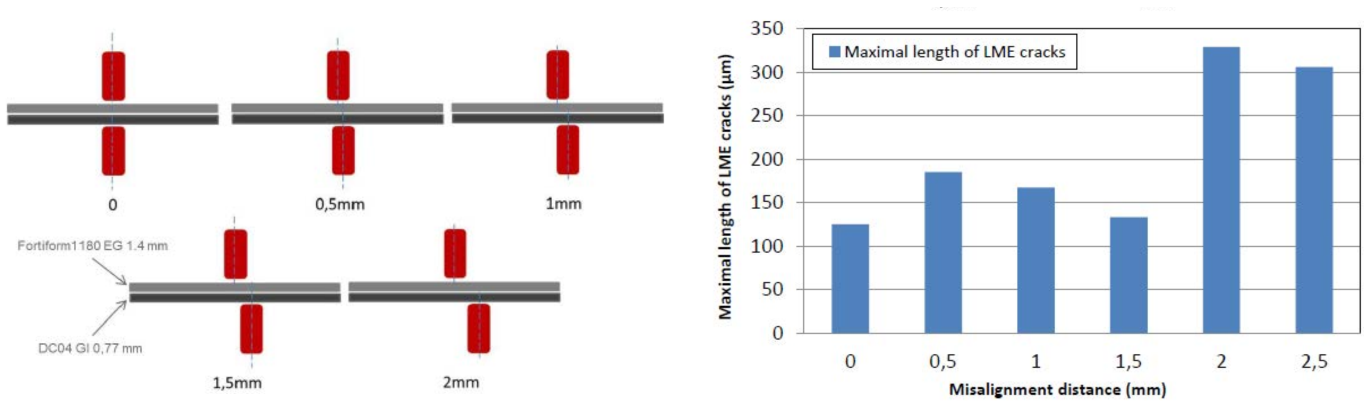

Figure 3. Impact of the lateral misalignment of the welding electrode on LME crack sizes occurrence.

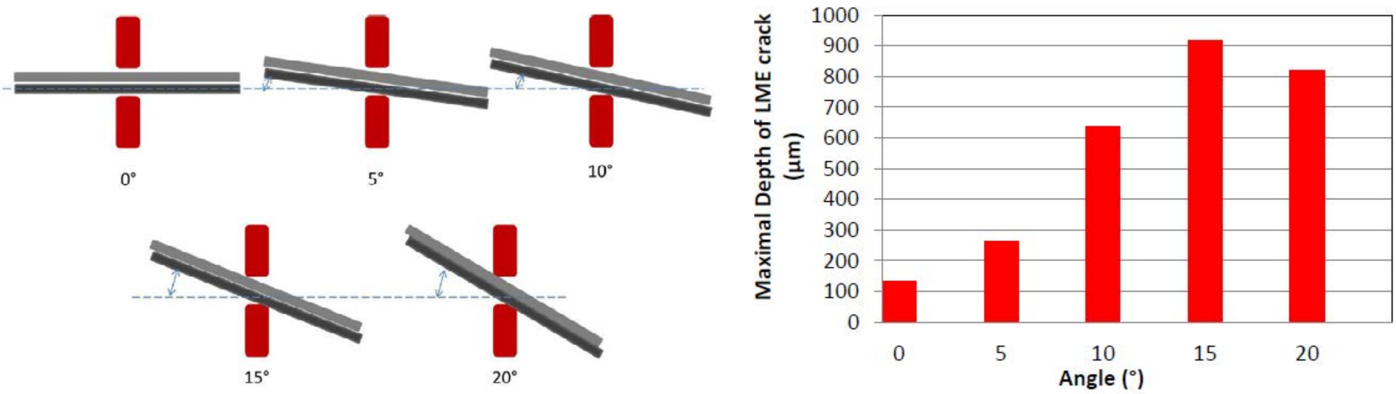

Figure 4 Impact of the angular misalignment of the welding electrode on LME crack sizes occurrence.

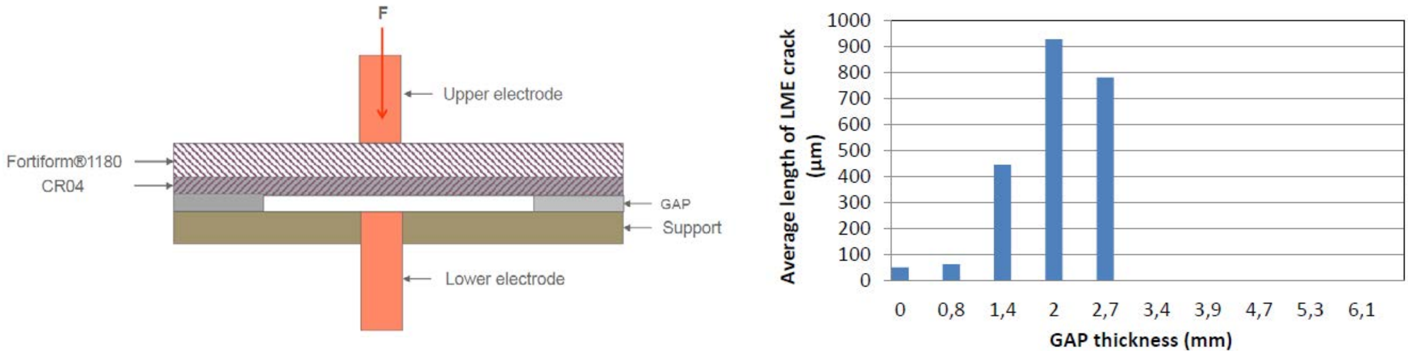

Figure 5. Impact of the clearance between the welding electrode and the sheet on LME significance.

The results obtained from the LME protocol for the 3-sheet stack-up Fortiform®1180 + two mild steel sheets) are displayed on Figure 8.

Without misalignment, the standard electrode shows poor results, with 70% of the spot welds having cracks deeper than 200 µm. In this condition, both the larger standard electrode (F1-20-10) and the novel tip geometry show satisfactory results, without any LME crack above 200 µm.

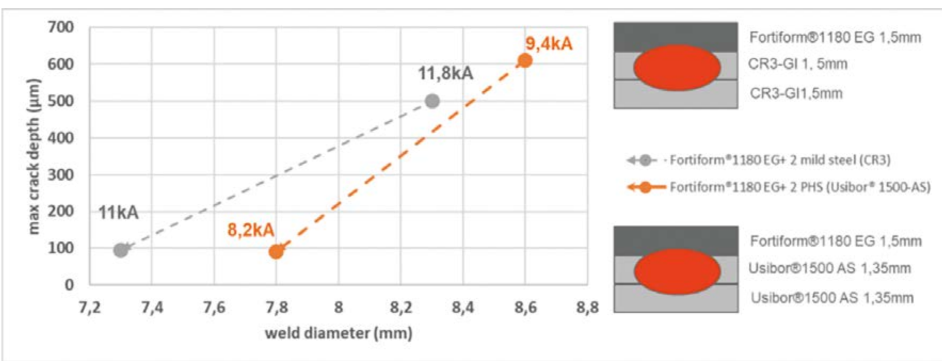

Figure.6. Impact of the welding current on weld and LME crack size for 2 3-sheets stack-up.

However, the 5° misalignment degrade the results with the reference electrode, and strongly deteriorates those obtained with the larger F1-20-10 tip, as compared to the standard condition. On the other hand, the results remain very satisfactory with the novel tip geometry: although slightly worse, still no crack deeper than 200 µm is detected.

Other spot-welding process modifications are claimed to be efficient in the literature by the University of Waterloo:

- Ramp down schedule recently proposed shows that crack index is reduced drastically [2] (Figure 9)
  - Aluminum foil between electrode and sheet shows interesting results on TRIP1100 avoiding higher crack depth[3] (Figure 10)

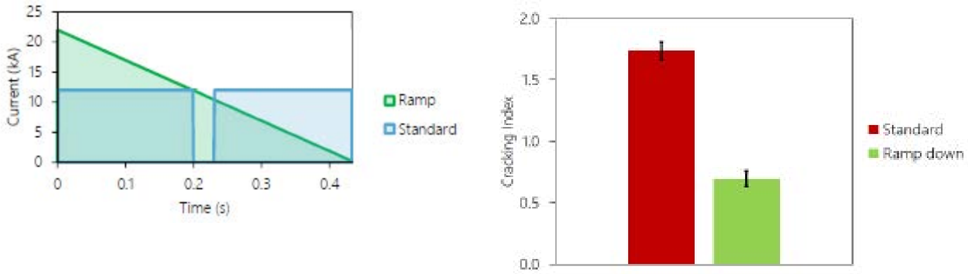

Figure 9. Ramp down schedule to reduce LME [2].

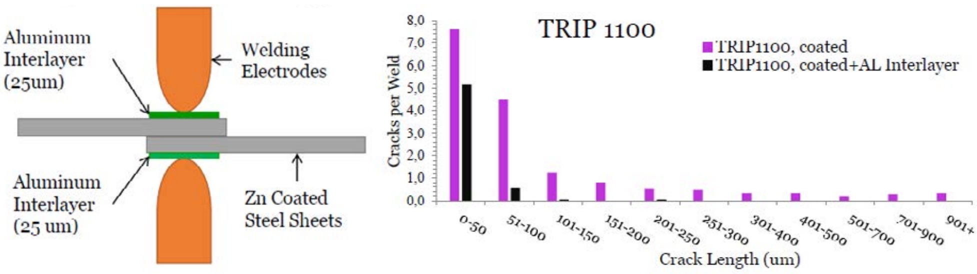

Figure 10. Ramp down schedule to reduce LME [3]

IMPACT OF LME CRACKS ON WELD STRENGTH

In order to evaluate the impact of LME cracks on the mechanical performances of welds, we have chosen a configuration associating an AHSS grade with 2 mild steels in order to ensure large crack sizes that can reach half the thickness of AHSS steel.

In Figure 11, it is shown that Cross Tensile Strength (CTS) and Tensile Shear Strength (TSS) are not reduced despite the presence of cracks up to half the thickness, and even if the fracture occurs on the AHSS steel side.

In Figure 12, several crash loads have been applied on welded structural parts, and on all the tested specimen even with high crack depth (up to 1/2 thickness). No detrimental behavior has been observed compared to non-cracked specimens. Crash force are similar without any decrease. Spot weld fractures always start from the bottom of the notch at the interface of the two sheets and are never initiated by the LME crack from the surface. And finally, it is shown in figure 13 that LME cracks do not decrease fatigue limit in Tensile Shear Strength (TSS) as fatigue cracks do not start from the LME crack at the surface; this is shown in the same conclusion for other loading modes mentioned above.

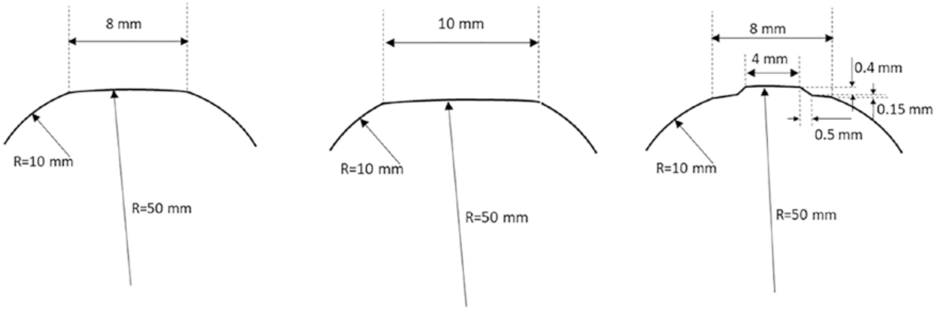

Figure 7: Schematic tip geometries F1–20–8 (left), F1–20–10 (middle), and novel (right).

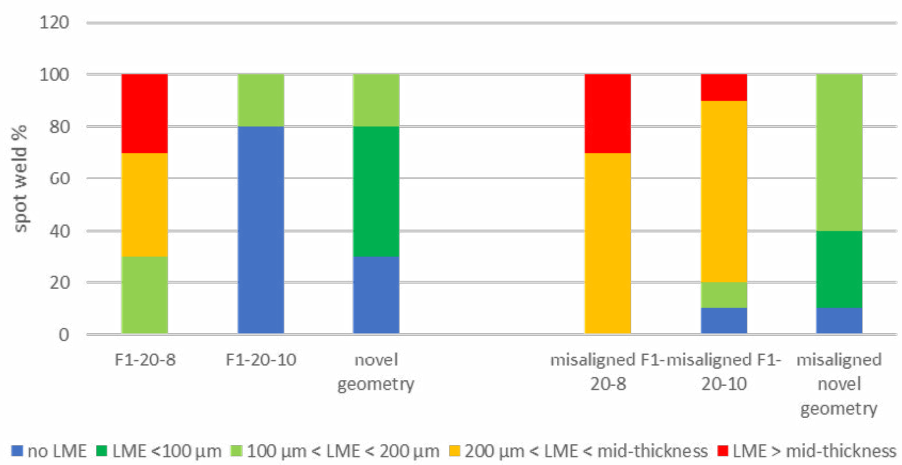

Figure 8 : Liquid Metal Embrittlement results for the 3-sheet stack-up, based on maximum crack depth in each weld.

DEVELOPMENT OF LME RESISTANCE AHSS PRODUCT

In this section, we will illustrate the improvements made in our recent development of Fortiform®1180 Q&P (Quenching and Partitioning) GI and Fortiform®980 Q&P GI. For these, we used the most severe configuration combining the Fortiform® grade with 2 thick mild steels welded at Imax. This new generation of Fortiform® has been optimized to significantly reduce sensitivity to LME. In Figure 14, we can see that the cracks have considerably decreased and other reference grades like DP600 and DP1180 are not free of cracks with these severe welding conditions.

CONCLUSION

Fortiform ®1180 shows very low LME sensitivity when welded in homogeneous or in heterogeneous configurations with other conventional AHSS (Dual Phase or Press Hardened Steel Usibor). Only small cracks (<100m) were observed for almost all these configurations. However, deeper cracks were observed when the Fortiform 1180 was welded with Mild or HSLA steel grades [4].

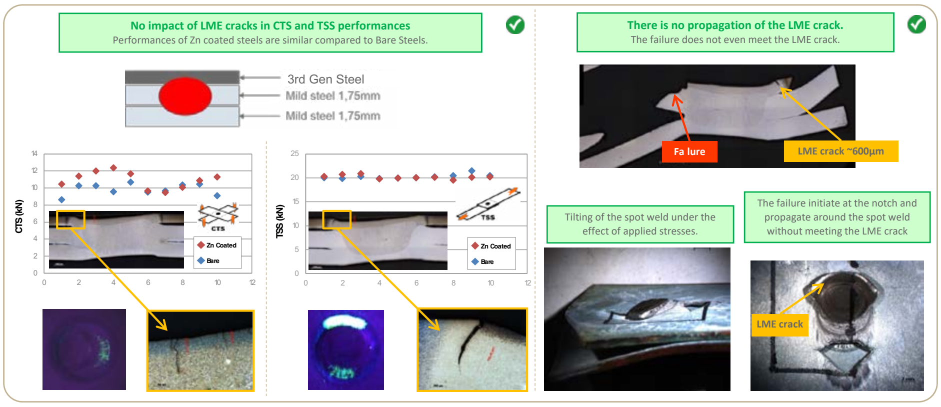

Figure.11. Impact of LME cracks on CTS and TSS.

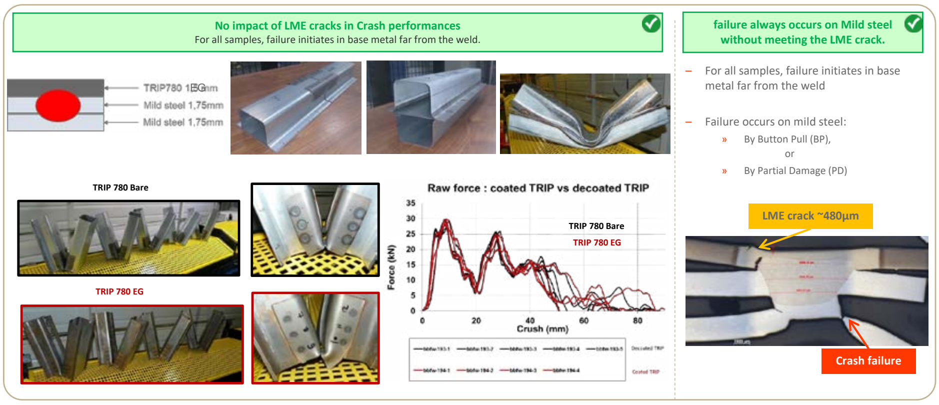

Figure 12. Impact of LME cracks on crash behaviour on welded component.

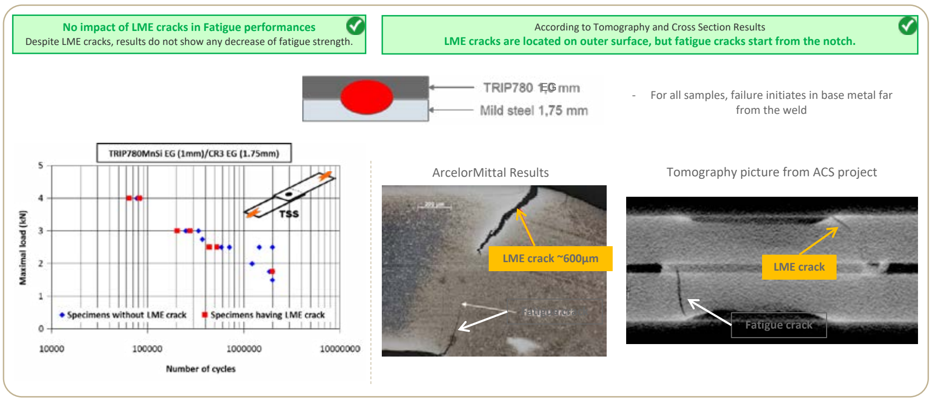

Figure 13. Impact of LME cracks on fatigue behaviour (TSS).

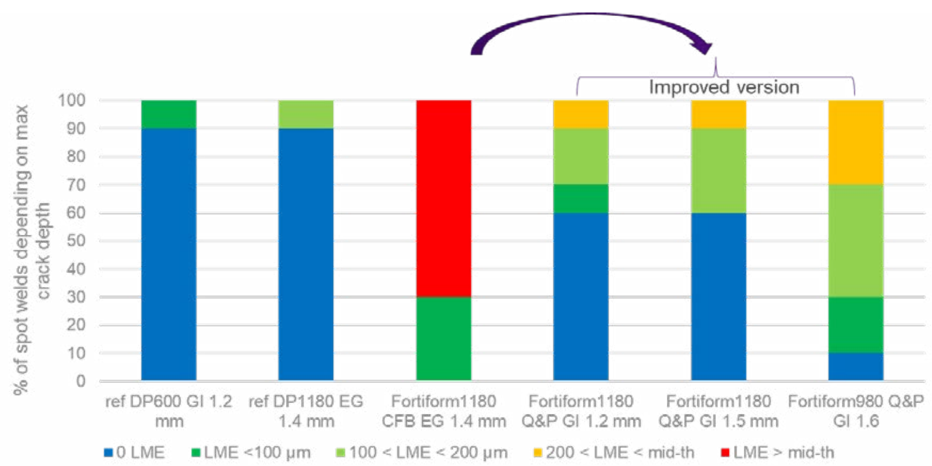

Figure 14. LME cracks distribution of Fortiform 1180-GI and Fortiform 980 GI with other references.

Industrial welding conditions increase the LME occurrence. Recommendations are given in this paper to limit their impact and reduce the cracks number and depth. Current intensity level and electrode tip geometry are the two main levers to reduce the size of LME cracks. Experiments demonstrated that no reduction of performance was found in CTS, in TSS in quasi-static and fatigue load but also in several crash loads for the maximal observed cracks sizes [5]. And finally, we have developed new LME-resistant Fortiform 1180 GI and Fortiform 980 GI, which show a considerable improvement in the most severe conditions.

References

[1] Thomas Dupuy, "A novel electrode tip geometry to mitigate Liquid Metal Embrittlement during resistance spot welding" Int. Inst. Weld. Do N° III-2064–22, presented at commission III intermediate meeting (online), february (2022).

[2] C. DiGiovanni, S. Bag, C. Mehling, K. W. Choi, A. Macwan, E. Biro, N. Y. Zhou, "Reduction in liquid metal embrittlement cracking using weld current ramping" Welding in the World (2019) 63:1583–1591

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[6] ISO 5821:2009, Resistance welding — Spot welding electrode caps, 2009

[7] International Patent application WO2020212741A1