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Liquid Metal Embrittlement in Resistance Spot Welding and Hot Tensile Tests of Surface-refined TWIP Steels

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Abstract. Automotive industry strives to reduce vehicle weight and therefore fuel consumption and carbon dioxide emissions. Especially in the auto body, material light weight construction is practiced, but the occupant safety must be ensured. These requirements demand high-strength steels with good forming and crash characteristics. Such an approach is the use of high-manganese-content TWIP steels, which achieve strengths of around 1,000 MPa and fracture strains of more than 60 %. Welding surface-refined TWIP steels reduces their elongation at break and produces cracks due to the contact with liquid metal and the subsequent liquid metal embrittlement (LME). The results of resistance spot welds of mixed joints of high-manganese-content steel in combination with micro-alloyed ferritic steel and hot tensile tests are presented. The influence of different welding parameters on the sensitivity to liquid metal embrittlement is investigated by means of spot welding. In a high temperature tensile testing machine, the influence of different parameters is determined regardless of the welding process. Defined strains just below or above the yield point, and at 25 % of elongation at break, show the correlation between the applied strain and liquid metal crack initiation. Due to the possibility to carry out tensile tests on a wide range of temperatures, dependencies of different temperatures of the zinc coating to the steel can be identified. Furthermore, the attack time of the zinc on the base material is investigated by defined heating periods.

1. Introduction

The automotive industry seeks for new economic and ecological solutions for new passenger cars to fulfill increasing comfort and safety requirements while complying with the tightening emission standards. The latter demand is mainly met by reducing fuel consumption. The manufacturers can achieve this objective through optimisation of the car engine and/or through reduction of the moving mass. Consequently, the lightweight plays an increasingly important role. Therefore, steel research materials are currently being developed that reach their deformation capacity under mechanical stress not only by dislocation glide, but also due to other deformation mechanisms which make a major contribution to ductility. In this context, a new development of high-manganese austenitic lightweight steels based on the Fe-Mn-Al-Si-C alloy system was introduced for the first time in 1998 by Georg Frommeyer at the Max Planck Institute for Iron Research. Due to a TRIP- and/or TWIP effect, these steels reach fracture strains up to 90 % and strengths up to 1,100 MPa with a simultaneous reduction of density compared to conventional steels, as shown in figure 1 [1, 2, 3, 4].



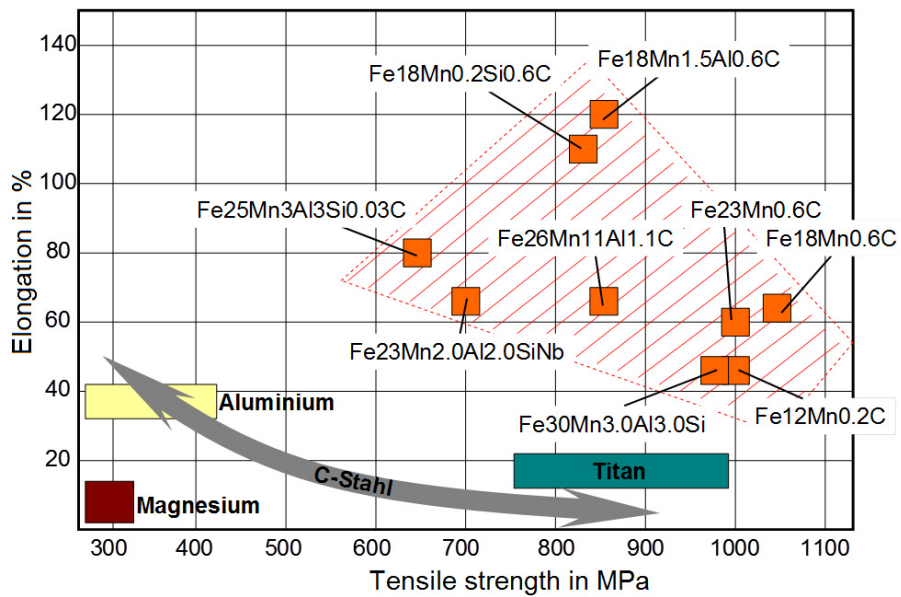


Figure 1. Tensile strength and deformation behavior of various metals [5].

When joining blanks in the auto body area, resistance spot welding is used predominantly. Usually unalloyed, but also alloyed steel sheets are processed. In mixed joints of ferritic and austenitic steels problems arise due to the following properties:

- Different composition of steels
- Different material structure
- Significantly different melting points, thermal expansion coefficients and electrical resistances [6]

These typical problems for black and white joints apart, when welding high-manganese-content steels to unalloyed steels, liquid metal embrittlement additionally occurs as follows. The molten zinc of the sheet coating enters locally particularly exposed areas along the grain boundaries in the material, where it leads to cracks. In the worst case, the course of the crack affects the entire thickness of the material, as seen in figure 2.

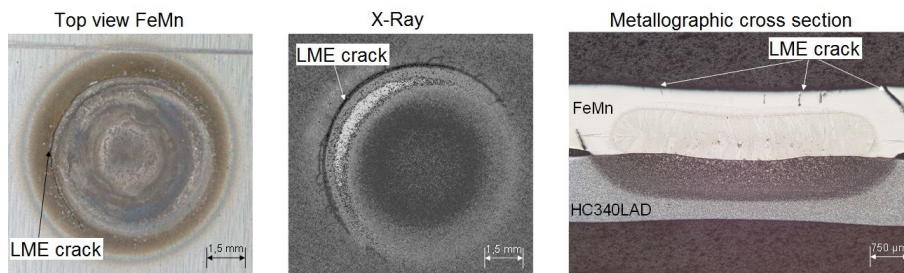


Figure 2. Liquid metal induced cracks in a mixed resistance spot weld.

It is proved that the liquid metal induced cracks occur due to high residual welding stresses in mixed joints and due to austenitic structures' sensitivity to liquid metal embrittlement.

2. Test materials

The tested high-manganese-content steel - hereinafter referred to as FeMn steel - is galvanized and has a thickness of 1.5 mm. The special feature of these steels is the pronounced TWIP effect. The twinning results in very high strength combined with very high fracture strain. Adding aluminium and silicon reduces the density. The ferritic joint partner is the galvanized microalloyed fine-grained steel

HX340LAD of 1.5 mm thickness. The mechanical properties and chemical compositions of both steels are shown in table 1 and table 2.

Table 1. Mechanical properties transverse to rolling direction.

Steel	Yield Strength (MPa)	Tensile Strength (MPa)	Fracture Strain (%)
FeMn	592	986	60
HX340LAD	405	471	30

Table 2. Chemical composition.

Steel	C (%)	Mn (%)	Al (%)	Si (%)	Ti (%)	Nb (%)	P (%)	S (%)
FeMn	0.590	15.5	2.2	2.010	-	-	0.002	0.001
HX340LAD	0.11	0.5	0.015	0.500	0.150	0.090	0.025	0.025

3. Test rig and test program

3.1. Spot welding machine

The welds were made with the pneumatic resistance spot welding machine PMS 11-3 of the company Dalex with control system MPS 15043 IQ. The machine has a maximum short-circuit current of 32.2 kA and a maximum electrode force of 6 kN, generated pneumatically. The welding current ranges were determined according to SEP 1220-2 with constant times and pulses as well as variable weld currents, electrode forces and types of electrodes. Only mixed joints were welded. All combinations were also welded with non-galvanized sheets in order to prove that the cracks occur due to LME caused by the zinc only, and not due to the hot cracking which originates from different expansion coefficients.

3.2. High temperature tensile testing machine

The high temperature tensile testing machine, as shown in figure 3, was developed, designed and manufactured at the ISAF. Here, the samples are subject to both mechanical and temperature stresses. The heat input in the specimen is performed by a high frequency alternating current with a frequency of 100 kHz and a maximum power of 20 kW. The test pieces are clamped in a fixed/fixed bearing and extended at a defined speed. Specimens with thicknesses up to 5.0 mm can be tested. The geometry is shown in figure 4. The load cell can measure loads up to 20 kN. The achievable peak temperature depends on the material. The elongation is measured by inductive displacement transducers. The measured values of time, temperature, load and displacement are analyzed with a computer.

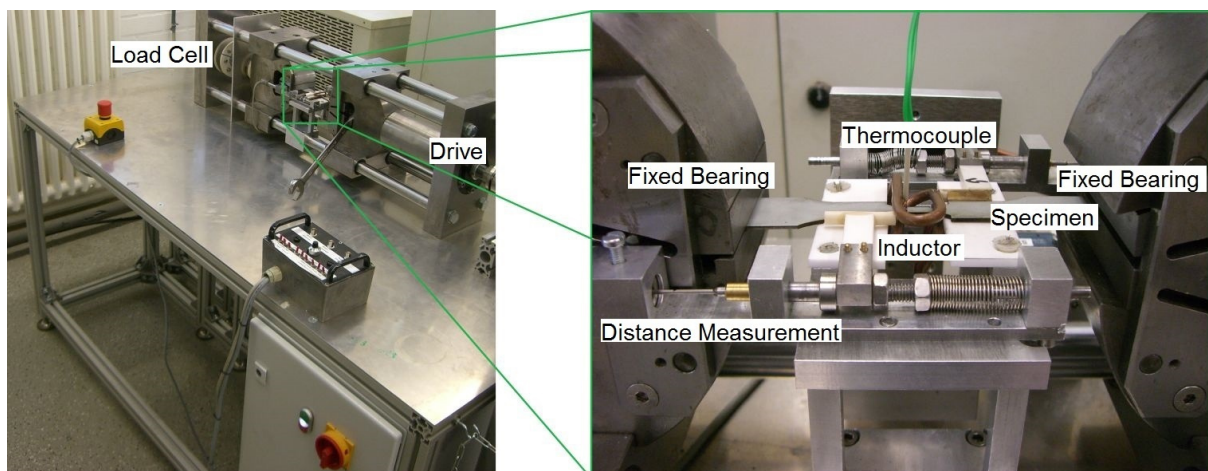


Figure 3. High temperature tensile testing machine with specimen chamber.

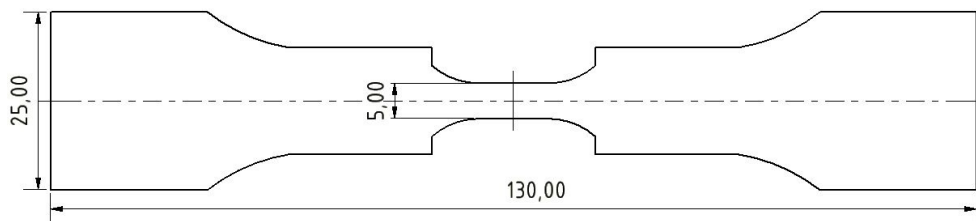


Figure 4. Specimen geometry for high temperature tensile tests.

4. Results

4.1. Influence of the zinc coating on the sensitivity to LME of spot-welded FeMn(+Z)/HX340LAD+Z sheet combinations

The determination of the relation between the cracks' length and position and the material condition, the current, electrode shape and electrode force was performed based on macro shots of the joints as well as on etched and non-etched metallographic cross section images. In the first test section, resistance spot welds were compared with and without zinc coating in order to study the influence of coating to the cracking. An overview of the influence of the zinc coating to the sensitivity to LME of the FeMn is shown in figure 5.

Welding tests were done with galvanized and non-galvanized FeMn and HX340LAD steel sheets. As a result, all tests with galvanized FeMn had LME cracks. No cracks occurred if both the FeMn steel and the HX340LAD steel were non-galvanized. Mixed joints in which only the HX340LAD steel was coated showed no cracks on the surface of the FeMn sheet. However, some few welds showed cracks in the cross section between the sheets. The zinc of the HX340LAD sheet could get into the non-galvanized FeMn and induced the LME crack.

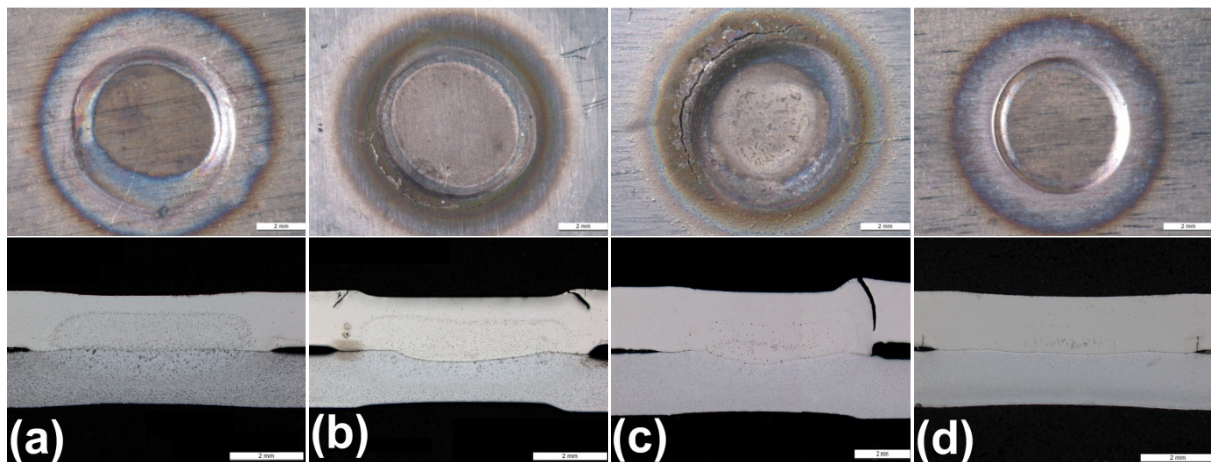


Figure 5. Macro shots as well as metallographic cross sections of spot welded mixed joints.

(a) FeMn/HX340LAD; (b) FeMn+Z/HX340LAD;
(c) FeMn+Z/HX340LAD+Z; (d) FeMn/HX340LAD+Z.

4.2. Influence of the energy input on the sensitivity to LME of spot-welded FeMn(+Z)/HX340LAD(+Z) sheet combinations

After examining the zinc influence on the sensitivity to LME, the energy input was analyzed. In this case, the tests were carried out exclusively on galvanized sheets. The minimum, medium and maximum currents of the detected welding current ranges were investigated with different electrode diameters and forces. It was discovered that the LME cracks increase in length as the current rises. The specimens showed no surface cracks when splatter occurred. Obviously shrinkage stresses were reduced, so that a residual stress field necessary for cracking was missing. However, the splatter created large cavities in connection with interdendritic extending cracks inside of such spot welds.

This was due to large volume shrinkage by the displaced material. Also the sheet failed at the joint line outside the weld nugget, which was caused by the bending of the sheets as a result of splashes. Table 3 shows the average crack length in mixed joints of FeMn+Z/HX340LAD+Z, welded with different electrode caps and forces.

Table 3. Crack lengths in mixed joints of FeMn+Z/HX340LAD+Z

Electrode cap (mm)	Electrode force (kN)	Average crack length (mm)
F16x20 5.5	4.5	12.6
F16x20 5.5	5.6	11.5
F16x20 8.0	4.5	8.1
F16x20 8.0	5.6	6.7

It was found that the cracks decrease in length with larger cap diameters and larger electrode forces, so they can be reduced down to 50 % compared to the smaller electrode caps and forces.

4.3. Influence of the electrode cap geometry on the sensitivity to LME of spot-welded FeMn(+Z)/HX340LAD(+Z) sheet combinations

The initiation of the LME cracks mostly takes place in the edge area of the electrode indentation on the sheet due to particularly high stresses in this area. For this reason, different types of electrode caps were tested. The idea was to reduce the tensions at the most stressed areas by larger electrode cap radii, as seen in figure 6.



Figure 6. Influence of different radii of electrode caps (schematic).

For comparison purposes, the influence of the electrode cap geometry was tested with constant parameters: electrode force 5.6 kN, welding current 6.7 kA. As shown in figure 7, three different diameters and geometries of electrode caps were used in addition to the standard types (4 and 5).



Figure 7. Different types of electrode caps.

Type 3 has an even surface and a diameter of 14 mm. It did not provide satisfactory results, since the current of 6.7 kA is not sufficient for an adequate heat development in the weld area. Increasing the current to 9.0 kA led to excessive spatter formation. When welding with rounded cap type 1, invariably sparks and splashes occurred due to the small contact area, so that these specimens were also not satisfying. The combinations of the flat and slightly crowned type 2 initially proved to be useful. The surfaces of the weld spot did not show any cracks on the edge. Metallographic cross sections of the joints uncovered, however, that the cracks moved inwards. In conclusion, the electrode cap geometry could minimize the size of cracking to a small extend, but could not completely prevent the cracks.

4.4. High temperature tensile tests

In addition to the influence of temperature, all test materials were mechanically tested for the present stresses. Knowing the influences of temperature, time and stress, the existent range of LME cracks was determined. Of major importance was the question whether the zinc had to be in molten state, above 420 °C, or whether it could penetrate even at lower temperatures along the grain boundaries into the base material by diffusion. High temperature tensile tests were carried out in 50 °C steps between 300 °C and 600 °C.

In the galvanized FeMn specimens, macro shots show LME cracks on the surface starting from 450 °C. This was also perceptible in the mechanical and technological characteristics. For example the values of tensile strength in comparison to galvanized and non-galvanized specimens were on one level up to a test temperature of 400 °C. From 450 °C on, and finally at the maximum test temperature for galvanized specimens of 600 °C, the values varied already by 50 MPa, as shown in figure 8.

To illustrate the superficial LME cracks, the fractured surfaces of the specimens of galvanized and non-galvanized FeMn sheets at test temperatures of 300 °C up to 600 °C were recorded. The specimens at 300 °C and 400 °C showed no cracks and an equally reduction of area in both conditions. From 450 °C on and most clearly at 600 °C, widening cracks could be observed. A reduction of area as happens in non-galvanized sheets did not occur. The reduction in area in both states at test temperatures up to the melting point of zinc is at the same level. With further increase in temperature, however, the curves move away from each other, so that the elongation at break of non-galvanized FeMn steel is at 48 % and the galvanized at 22 %.

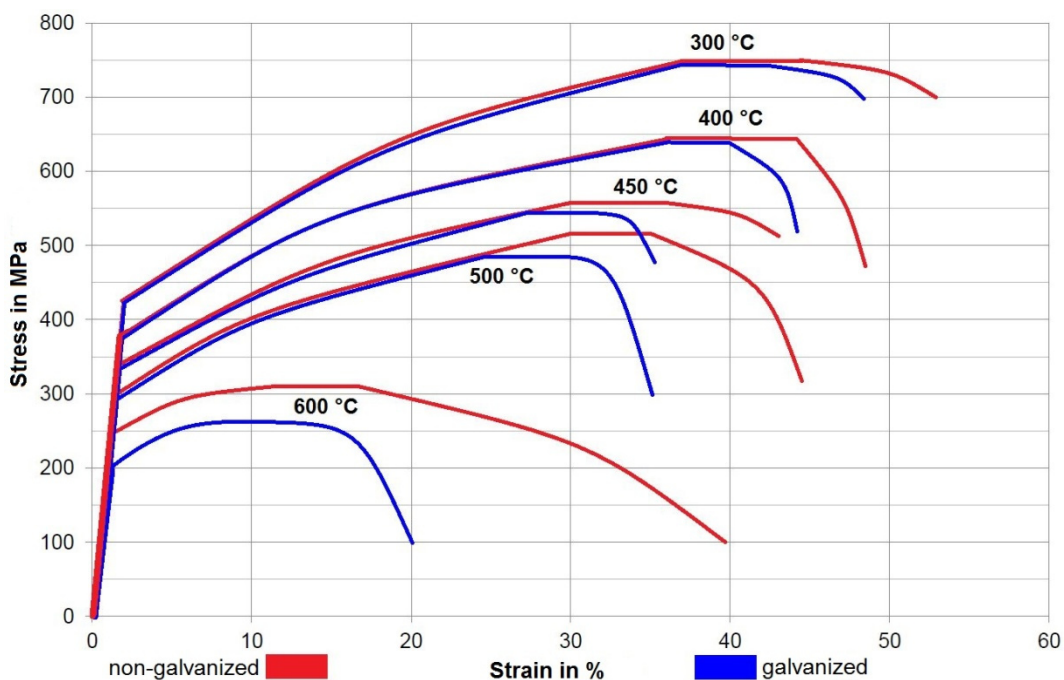


Figure 8. Stress-strain-diagram of high temperature tensile tests with galvanized and non-galvanized FeMn steel.

In a further step, the influence of strain on the sensitivity to LME was examined by tensile tests on galvanized and non-galvanized FeMn specimens at elevated temperatures of 450 °C and 500 °C.

For the respective temperature levels, three different yield strengths were considered:

- just below $R_{p0,2}$
- just above $R_{p0,2}$
- 25 % total elongation

The non-galvanized specimens had no cracks regardless of temperature or yield stress levels. Also in galvanized specimens, no cracks were determined below the yield point. However, at 450 °C and just above the yield point, the galvanized specimens had cracks of an average length of 2 μm. At 25 % total elongation, the cracks extended up to 5 μm. Galvanized samples at 500 °C and just above the yield stress evinced cracks with an average length of 10 μm. At 25 % total elongation, significantly more cracks occurred with an average length of 8 μm. In addition, there were sporadic cracks with a length of 100 μm. The increased mechanical load on the material in combination with the high temperature led to a sudden rise in crack length.

Further investigations were carried out with various pre-elongations, dwell temperatures, dwell stresses and cooling media. The tests showed no dependence on the dwell time and no cracks.

The pre-elongation of the specimens leads to cold working of the material. The tensile strength could be partially increased from the original value of 1,000 MPa up to 1,300 MPa. This cold working did not affect the sensitivity of the FeMn steel to LME.

In further tests, the specimens were heated up to 500 °C and then elongated at this temperature level until a stress of 450 MPa was achieved. At this temperature and stress level the specimens were maintained again for different dwell times (0.5 minutes, 1 minute, 1.5 minutes, 2 minutes...5 minutes). Thereafter, the sample was released from load and heat and cooled down in ambient atmosphere. Finally, a tensile test was carried out at room temperature. Here, a significant influence on the yield strength and reduction of area was found and is shown in figure 9.

The tests have shown that the thermal treatment of the galvanized material significantly affects the yield strength and the reduction of area. Depending on the dwell time, the yield strength drops by 100 MPa down from 455 MPa at 0.5 min to 355 MPa at 5 min. The reduction of area decreases from 48 % at 0.5 min down to 33 % at 5 min. The tensile strength is not affected.

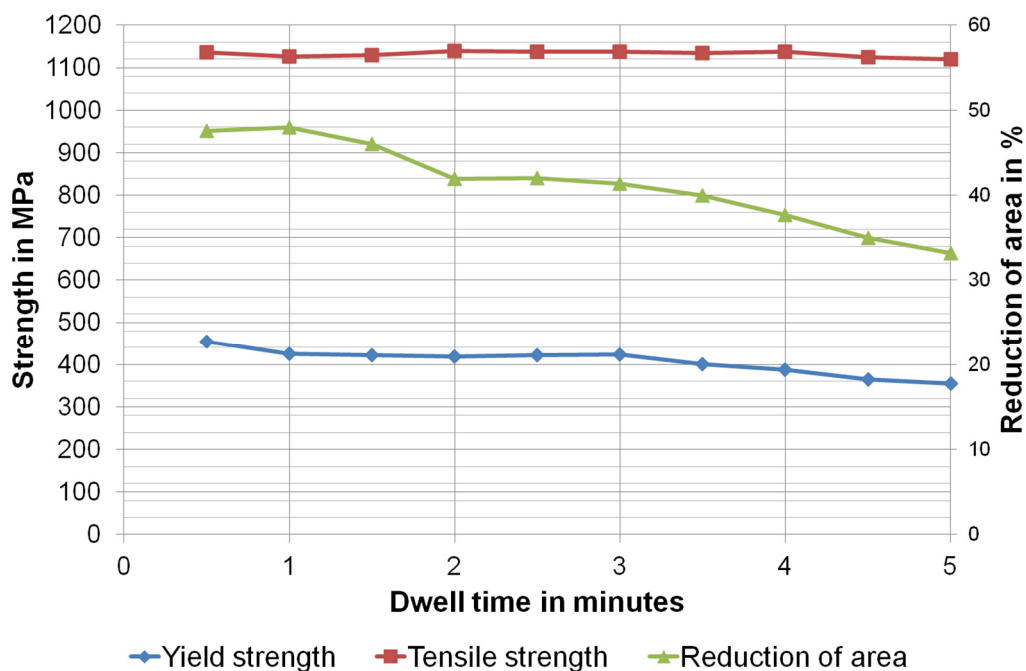


Figure 9. Strength and reduction of area of the galvanized FeMn specimens elongated to 450 MPa and heated to 500 °C depending on the dwell time.

5. Summary and conclusion

Liquid metal induced cracks occur during spot welding of high-manganese steel and microalloyed fine-grained steel HX340LAD with 1.5 mm thickness, whenever at least one of the sheets is galvanized. No cracks occur, when both steels are non-galvanized. Using larger electrode caps and

forces reduced the crack lengths down to 50 %. Also, the use of different electrode cap geometries could not completely prevent the cracks.

The construction of the high temperature tensile testing machine has laid the foundation for systematic determination of the LME cracks' existence range regardless of the welding process.

At 600 °C, the tensile strength and the elongation at break of galvanized FeMn steels are already lower by 20 % and 50 % than the values of the non-galvanized material.

At a temperature of 500 °C and stress of 450 MPa, the increased mechanical load on the material leads to a sudden rise in crack length.

Experiments with different dwell times have shown that these temperatures and stresses result in a strong decrease of the yield strength and reduction of area.

Further work is necessary and will be performed, in order to achieve ideal joints completely without liquid metal induced cracks or whose length is at least reduced to a tolerable minimum.

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