Scripta Materialia 114 (2016) 41–47

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Liquid metal embrittlement-free welds of Zn-coated twinning induced plasticity steels

Rouholah Ashiri [a,b,*], Morteza Shamanian [a], Hamid Reza Salimijazi [a], Md Anwarul Haque [b], Jin-Hee Bae [b], Chang-Wook Ji [c], Kwang-Geun Chin [d], Yeong-Do Park [b,*]

[a] Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Advanced Materials Engineering, Dong-Eui University, Busan 614-714, Korea
[c] Department of Materials Science & Engineering, The Ohio State University, Columbus, OH 43221, USA
[d] POSCO Technical Research Laboratories, Gwangyang 545-090, Korea

ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 24 November 2015
Accepted 24 November 2015
Available online 17 December 2015

Keywords:
Twinning induced plasticity (TWIP) steels
Grain boundary embrittlement
Simulation
Resistance spot welding
Crack-free welds

ABSTRACT

The high electrical resistivity of twinning induced plasticity steels makes their resistance spot welding difficult and limits their weldability. Meanwhile, liquid metal embrittlement of Zn-coated twinning induced plasticity steel welds is one of the most important challenges facing the scientific community. Liquid metal embrittlement also limits weldability of the steels and influences the mechanical response of welds. This work addresses this challenge by developing an innovative pathway to obtain liquid metal embrittlement-free welds which is able to extend the weldable current range of the steels. Simulations demonstrate that the method can perform a smart management of heating which is critically required to obtain embrittlement-free welds.

The global demand for safe, environment-friendly and energy-efficient vehicles is the driving force for development of automotive steels by steelmakers. In reaction to this demand, advanced high strength steels have been developed for automotive structures [1–2] which have simultaneously been the subject of significant interest and the focus of a number of recent researches [1–5]. Last decade, a significant increase in the research activity has been dedicated to the high manganese austenitic, so-called twinning-induced plasticity (TWIP) steel [3,6–9] as a good candidate for structural parts in automotive body [10–11].TWIP steels are normally zinc coated to resist the corrosion. Favoring twinning as the predominant deformation mechanism, strength–ductility synergies induced by the dynamic Hall–Petch effect [12] delaying the occurrence of necking [13–14] are responsible for outstanding mechanical performance of these steels. However, the susceptibility to embrittlement induced by hydrogen [15–16] and liquid zinc [17] has been reported for formed and Zn-coated sheets of these steels, respectively. Recent researches have shown that aluminum significantly helps alleviate hydrogen embrittlement of TWIP steels [18–20], but their liquid zinc embrittlement still has remained a challenge for the scientific community.

The main focus of the above referred researches [6–20] was the concepts of mechanical performance or alloying of TWIP steels. One key point [21], weldability, has been neglected in those researches. Since enough weldability is required to guarantee the use of the TWIP steels in the automotive, this issue should be considered in order to use the excellent potential of TWIP steels in the autobody. This issue faces some serious challenges which need to be addressed [22]. Most of the autobody components are made by sheet materials and resistance spot welding is the main joining process used in assembly lines of automotive industry, a trend that is expected to go on for the foreseeable prospect [23]. Therefore, resistance spot welding of Zn-coated TWIP steels should be examined before their application in the autobody. Our results have shown that Zn-coated TWIP steels are susceptible to liquid metal embrittlement (LME) induced by liquid zinc when they are subjected to the resistance spot welding process [24]. This susceptibility can influence the reliability and corrosion resistance of the welds and needs to be suppressed. In the absence of any solution for this challenge, this work aims to develop an innovative pathway to obtain LME-free welds of Zn-coated TWIP steels. Our results demonstrate that a smart management of heating is critically required to obtain LME-free reliable welds and also to extend the weldable current range of TWIP steels. We believe that the method developed here can easily be used to obtain LME-free reliable welds of other susceptible advanced high strength steels which are susceptible to embrittlement induced by liquid zinc.

---

* Corresponding authors.
E-mail addresses: ro_ashiri@yahoo.com, ashiri@deu.ac.kr (R. Ashiri), ypark@deu.ac.kr (Y.-D. Park).

http://dx.doi.org/10.1016/j.scriptamat.2015.11.027

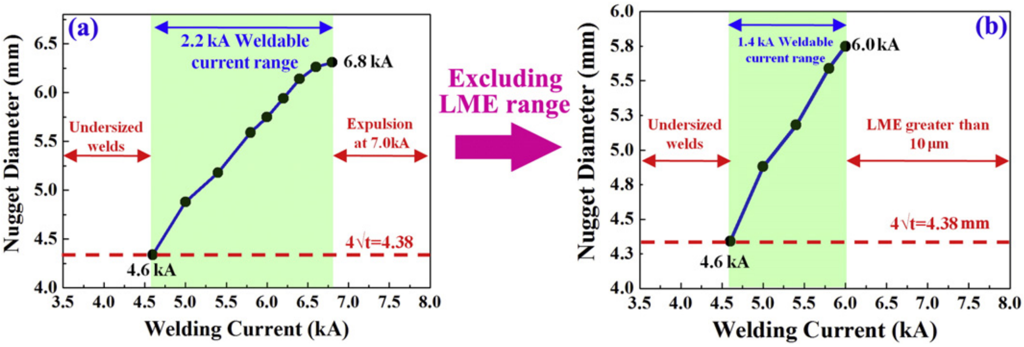

Fig. 1. (a) The weldable current range of electrogalvanized TWIP steels in the presence of LME cracks and (b) with excluding LME range from the weldable current range.

The chemical composition of the investigated steel was Fe–15.7Mn–0.5C–2Al (wt.%) and minor alloying elements which exhibit a good combination of strength and ductility (yield strength of 560 MPa, ultimate tensile strength of 920 MPa and elongation of 46%). This steel is fully austenitic at room temperature and exhibits no phase transformation in the studied temperature range. Four sets of specimens were used: bare TWIP steel sheet as control specimen, galvanized (pure Zn, 10 μm thick), galvannealed (10 μm thick) and electrogalvanized (Zn–12 wt.%Ni, 10 μm thick) TWIP steel sheets of 1.2 mm thick to study the effect of liquid zinc and cracking resistance of different coated steels. The cold rolled TWIP steels were subjected to a solution treatment at a temperature higher than 800 °C for more than 1 min before the coating process. The contact with the liquid zinc arose from melting the zinc coating during heating induced by resistance spot welding. The specimens were cut into samples for welding and then were cleaned properly with ethanol to remove dirt and oil before welding. Welding was carried out using a pedestal type medium frequency DC inverter spot welder with a 6 mm tip diameter of Cu–Cr dome-radius type electrode under a constant water-cooling rate of 6 l/min. The welded samples were cross sectioned, mounted and then polished to 1 μm diamond paste. Then the cracking susceptibility of the steels was observed and measured optically at 200× magnification using polished samples and their susceptibility was quantified by the maximum length of crack found anywhere of the welds. The cracking susceptibility can be quantified by different criteria including total numbers of the cracks, total length of the cracks and maximum crack length [25]. Since the longer cracks need less energy to propagate and results in early failure, so the last one was selected for the current work. LME cracks were also investigated by field-emission electron probe microanalysis (FE-EPMA). Due to the special weld geometry in resistance spot welding process which makes the weld zone inaccessible, in order to determine stress history and thermal cycle experienced during resistance spot welding, simulations were performed with a finite element software, SORPAS® [26], which has been dedicated to the simulation of resistance spot welding processes..

Generally, LME is the phenomenon where a solid metal is embrittled in the presence of liquid metal and tensile stress which can result in the premature brittle fracture or loss in ductility of a usually ductile metal [16,24,26–27]. LME phenomenon has mainly been studied using mechanical testing while specimens are in contact with liquid metal (bath of embrittler) at a constant temperature [17]. Although this approach may be useful for understanding the nature of LME phenomenon; however such conditions are not met in a real welding experience. From a more important, and practical point of view, it is critically required to assess LME susceptibility of TWIP steels in the resistance spot welding process which is the most widely used process in assembly lines of the automotive industry. This approach can guarantee the application of TWIP steels in the automotive industry. This work concerns this approach.

To access the weldability of different TWIP steels, experiments were performed with a single-pulse resistance spot welding using electrode force of 2.6 kN, welding time of 16 cycles (266.67 ms) at different welding currents. Fig. 1a shows weldable current range of the electrogalvanized TWIP steel sheets used in this work. The nugget size and expulsion are main criteria limiting weldable current range of electrogalvanized TWIP steels. The current range satisfying the minimum 4.38 mm nugget diameter ($4\sqrt{t}$ where t is the thickness of the sheet) to welding current just before expulsion was considered as weldable current range. It has been shown [24] that there are critical nugget diameter and supercritical area for LME of Zn-coated TWIP steels. Therefore, it is expected to see zinc induced embrittlement in the big enough nuggets (or high enough welding currents). Our observations confirmed this expectation. The reliability and mechanical performance of the welds are affected with the growth of these cracks by the vibrations of a car. According to GWS-5A standard [28], in the supercritical LME area, cracks bigger than 10 μm are not acceptable. Therefore, the welds with LME greater than 10 μm are not sound and welding currents resulting in such cracks should be excluded from the weldable current range. Fig. 1b shows the modified weldable current range for the electrogalvanized TWIP steel showing the effect of LME on the weldable current range. Significant effect of LME on the weldable current range is clearly seen in Fig. 1. Similar experiments were performed for other TWIP steels and the related results have been shown in Table 1. Although this table indicates that LME susceptibility of TWIP steels is dependent on their coating types, however as a general finding, LME phenomenon significantly affects the weldability of the Zn-coated TWIP steels boldfacing the significant importance of the possible solutions to this challenging issue. From Table 1 it can be said that galvanized TWIP steel is the most susceptible one to embrittlement and LME reduces about 77.8% of its weldable current range. The conditions used in

Table 1
Effect of LME phenomenon on the weldable current range of TWIP steels with different coating types.

Experimental alloy	Weldable current range in the presence of LME (kA)	Weldable current range excluding the LME range (kA)	Reduction in the weldable current range induced by LME (%)
Bare TWIP steel	2.5	No LME so 2.5	0
Electrogalvanized TWIP steel	2.2	1.4	36.4
Galvannealed TWIP steel	1.8	1.0	44.4
Galvanized TWIP steel	1.8	0.4	77.8