Characterization of bond line discontinuities in a high-Mn TWIP steel pipe welded by HF-ERW

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A B S T R A C T
In this work, the microstructure and defects in a high-frequency electrical resistance welded (HF-ERW) pipe of high-Mn twinning-induced plasticity (TWIP) steel were characterized. The microstructure of the base metal and the bond line were examined using both optical microscopy and scanning electron microscopy. The features of the bond line were similar to those of conventional steel. Simultaneously, the circumferential ductility was evaluated via a flaring test. It was concluded that the deterioration of the circumferential ductility in a high-Mn TWIP steel pipe was caused by irregular shaped oxide defects and a penetrator that had been formed during welding. Specifically, the penetrator, which is composed of MnO and Mn2SiO4, was found to be the most influential on the circumferential ductility of the welded pipe. The penetrator was analyzed using both an electron probe micro analyser and transmission electron microscopy, and the formation sequence of the penetrator was evaluated.

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1. Introduction
With the progression of the natural gas industry, the so-called shale gas revolution, various industries such as chemical and steelmaking have been affected both directly and indirectly [1–4]. Especially in the pipe industry, the demands for casing and tubing pipes called oil country tubular goods (OCTGs) have increased due to the shale gas mining [3–9]. Meanwhile, development of the OCTG is ongoing not only for use in harsh mining environments at considerable depths but for obtaining various sizes from a sole pipe through expanding method. Highly-formable steels have been naturally required for applying on-site pipe expansion at oil fields [7,9–11].

Given that background, high-Mn twinning-induced plasticity (TWIP) steel is one of the candidate materials for the OCTGs because of its superior balance of ductility and strength [12–15]. By virtue of its higher manganese content, which stabilizes the austenitic matrix at room temperature and produces lower stacking fault energy (SFE), it is possible to achieve SFE of between 15 and 40 mJ/m². With its lower SFE producing substantial twinning during plastic deformation, it exhibits higher strain hardening rates leading to ultimate tensile strengths of about 800 MPa and total elongations exceeding 60%. However, it has been utilized only in limited areas of automotive industry and cryogenic environments due to its high susceptibility to hot cracking during argon welding [16–18].

A high frequency electrical resistance welding (HF-ERW) process is used in seam welding for steel pipes [19–25]. In this process, continuous rolls of various sizes curl up in a circular tube from an uncoiled strip, and both edges of the strip are forged together and are heated to over the melting point by Joule heating. This rapid heating can arise from both the influence of a skin and a proximity effect. The molten metal with oxide particles is pushed out from the edges by the electromagnetic pressure [20,22,23]. The weld zone of HF-ERW is called the “bond line” because it seems like a very long single line. This is possible due to a continuous process of forming and welding, and this process has advantages with the aid of its high productivity and energy efficiency.

To the best of the authors’ knowledge, application of the HF-ERW process to high-Mn TWIP steels has not been reported previously. The “heated by resistance” phenomenon was first described by J. Joule in the mid-nineteenth century, and HF-ERW was introduced by H. B. Osborne, Jr. in 1956 [19], but it was called continuous seam welding. Basic research about the welding phenomena was first performed by H. Haga et al. [22,23] using a fast camera. They classified three types of welding phenomena that arise due to various welding conditions, and argued that defects were formed according to what the type of phenomena occurred. It was decided by function of the values of the approaching rate and receding rate to the removal of molten metal \(V_a\) and \(V_r\). Among the defects, penetrator, defect which was continuously arranged along the bond line, is a slag inclusion that is produced when molten slag is drawn into the gapped zone in the returning process of the molten metals. J. Choi [21] and C. Kim et al. [25], also using a fast camera, had closely investigated the welding phenomena in terms of the electromagnetic force. They concluded that penetrator formation...
is mainly influenced by a shape or length of narrow gap, which are strongly affected by electric current. Because of a capillary force, the narrow gap was refilled with molten metal containing oxides, and then the oxides are remained in the bond line. Meanwhile, H. Ichihara et al. [24] researched the weldability of stainless steel in inert gas atmosphere and insisted that it dramatically widens the appropriate range of welding. Post-weld heat treatment (PWHT) to normalize the bond line for ferritic steels has been studied by P. Yan et al. [20,26]. This focuses on the transformation of the matrix structure in the bond line rather than the reduction of defects for line-pipe steels. In addition, Thermatool Corp., which is the fabricator of the ERW pipe mill, has published various papers that present fundamental researches, case studies and applications [27,28]. As mentioned previously, however, there has not been a previous investigation of high-Mn austenitic TWIP steels in studies of HF-ERW.

This study reports the first results of application of the HF-ERW process to the seam welding of high-Mn austenitic TWIP steel pipe. The microstructural transitions in this steel caused by metal flow during welding were investigated. To evaluate the circumferential ductility of the welded pipe, a flaring test was conducted. After the test, various defects were investigated and classified to evaluate the deterioration factors of the welded seam i.e. bond line. Microstructural analysis was also performed to investigate the existing theory regarding the mechanism of defect formation during the HF-ERW process.

2. Materials and experimental procedures

For the present investigation, a hot rolled coil with a thickness of 3 mm was prepared and slit to make a skelp with a small pipe diameter of 88.9 mm (3.5 in). The chemical composition of the base metal used in this study is shown in Table 1. The skelp with this composition was continuously uncoiled and roll-formed, and then it was welded to join its both sides of the edges using a welding condition as given in Table 2. The parameters were selected to apply relatively lower power range and similar line speeds, and the shielding gas is used in order to reduce oxygen level below 5% in the atmosphere [22,25,29]. The specimens were cut and prepared by grinding with 100, 600, and 2000-grit SiC paper, followed by mechanical polishing using 1-μm diamond colloidal powder (Allied Product Inc.). All of the specimens were prepared for analysis in the rolling direction, RD, as illustrated in Fig. 1a (for reference, TD and ND are the transverse and normal directions, respectively). To analyze a cross-sectional view of the bond line, a flattening test was conducted. After the test, various defects were investigated and classified to evaluate the deterioration factors of the welded seam i.e. bond line. Microstructural analysis was also performed to investigate the existing theory regarding the mechanism of defect formation during the HF-ERW process.

X-ray diffraction (XRD, D/Max-2500, Rigaku) analysis was carried out using a Cu Kα source in order to determine the crystalline phase of the base metal. The patterns were obtained from 20 to 80° 2θ using a step size of 0.02° 2θ and 0.25 s per step. To evaluate the circumferential ductility of expandable pipes, a flaring test was conducted on a flaring tool with 60 degrees of conical die at room temperature, as illustrated in Fig. 1b. In this test, a mechanical constraint was applied in a constant moving rate (0.5 mm/s) of the pipe segments (length, l = 100 mm, diameter, d = 88.9 mm, and thickness, t = 5.5 mm). The test was carried out to validate the limit of the expanded diameter before cracking occurred in the welded pipes. After conducting the test, to analyze the deterioration factor of the circumferential ductility, the fracture surfaces were examined using FE-SEM. The formation mechanism of the defect during the HF-ERW process was analyzed by field emission transmission electron microscopy (FE-TEM, JEM-2100F, JEOL) after sample preparation using the focused ion beam (FIB) lift-out method. Analysis was performed in scanning TEM mode using a bright-field detector (BF-STEM).

3. Results and discussion

3.1. Microstructure

The matrix structure of the base metal shown in Fig. 2a is fully austenite, as confirmed by XRD patterns in Fig. 2b. From a linear intercept method for measuring a mean grain size [30], the austenitic grain size was 6.6 μm with elongated MnS aligned in the rolling direction and some inclusions. Because of the SFE of 23.7 mJ/m² based on the thermodynamic model proposed by Olson and Cohen for this composition, the austenitic grain is expected to deform on the twinning mechanism, diminishing the imposed strain energy [13,15]. Supporting this, Fig. 2c shows that mechanical twinning occurred in order to release the stress during roll forming. The corresponding selected area electron diffraction (SAED) pattern is shown in Fig. 2d. This SAED pattern with [011] zone axis gives evidence of the existence of the twin system. Due to strain hardening, it is expected for the expanded pipe to exhibit better mechanical properties [14].

Table 1

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Fe (wt.%)</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>Cr</th>
<th>Ni</th>
<th>S + P</th>
<th>Ti</th>
<th>V</th>
<th>Nb</th>
<th>Mo</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWIP steel</td>
<td>Bal.</td>
<td>0.3</td>
<td>24.6</td>
<td>0.3</td>
<td>0.01</td>
<td>&lt;5</td>
<td>0.1</td>
<td>0.015</td>
<td>0.005</td>
<td>0.005</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 2

Details of the HF-ERW parameters used to make pipe seam welds for joining TWIP steel in the present study.

<table>
<thead>
<tr>
<th>Welding process</th>
<th>Line speed</th>
<th>Heat input (power)</th>
<th>Squeeze out</th>
<th>Shielding gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF-IW</td>
<td>16–18 m/min</td>
<td>65–70 kW</td>
<td>2.0 mm</td>
<td>Ar</td>
</tr>
</tbody>
</table>
small size, it has been reported that the degradation in the HAZ that occurs during HF-ERW is important [11].

Unlike the decarburized layer in the weld zone of conventional steel, the contrast between the bond line and the base metal was based on the dendritic structure within the bond line in this study, as shown in Fig. 3c. In ferritic steels, the decarburized layer is caused by the difference in the carbon solubility of ferrite and liquid metal [31]. Since an austenite generally has higher carbon solubility than a ferrite, it is unlikely that a decarburized layer would appear. Although the HF-ERW process had a rapid cooling rate, columnar and equiaxed dendrites grew toward the center of the bond line due to the effects of both the segregation of high alloying elements and the low melting temperature [16]. The dendritic structure in the bond line is an undesirable phenomenon related to the metallurgical bonding formed by breaking up the interface between the skelp edges, but is unavoidable due to the aforementioned effects.

Comparing Fig. 3a and b, the penetrator defect occurred in the same direction as the recession of the molten metal. Typically penetrator are visible not only with optical microscopy, but to the unaided eye in an un-etched state, as shown in Fig. 3d. The penetrator was formed in some cases at random locations on the pipe. These defects are generally induced in the third type of welding, i.e. values of $V_a$ is lower than $V_r$. In this type of welding, the length of narrow gap increase with the increase of heat input, and a comet shaped narrow gap is formed due to Lorentz force variation on the edge wall [21–23,25]. This comet shape of the narrow gap strongly affects the penetrator formation because molten metal

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**Fig. 1.** Schematic diagram of experiments: (a) cross-section view analysis of the bond line in the as-welded pipe, and (b) apparatus and technique for the flaring test.

**Fig. 2.** (a) SEM image of the base metal, (b) X-ray diffraction pattern of the matrix, (c) TEM bright field images taken from strained samples, and (d) SAED pattern of the grain in (c) (the solid and dashed lines correspond to each of the twin systems, respectively).
can be easily re-entered. However, even if steady state conditions with equal values of $V_a$ and $V_r$ are maintained, namely the second type of welding, the penetrator formation can occur. In addition, under the influence of the high concentration of Mn that has a relatively higher affinity for oxygen than Fe, it is expected that the penetrator easily occurs.

3.2. Flaring test and fracture morphology

In the flaring test, cracking occurred when the welded pipe was flared at about 13%. Compared to stainless steel pipe that has a flaring performance of 25% despite its non-outstanding elongation [35,36], TWIP steel pipe is expected to have better performance because of its excellent elongation approaching nearly 60–95% [12–14]. For improvement of the circumferential ductility, deterioration factors were characterized by fractography in a SEM. Fig. 4 shows the SEM images of the fracture surface. The aforementioned MnS stringers, which were elongated in the rolling direction, existed on the fractured surface of the base metal, as shown in Fig. 4a.

Cracking occurred preferentially in the interface between the matrix and inclusions due to the unstable region [37]. On the other hand, it is possible to distinguish between the crack path propagating along the bond line and the base metal due to its stretched grain structure. Fig. 4b shows that the non-uniform dimple fracture in the bond line was caused by nano-sized carbides and oxides inside the voids. Given this perspective, distribution map of bond line at fractured surface is suggested in Fig. 4c. Both the region A (red area) and region B (yellow area) indicate the bond line, while the region C (black area) indicates the base metal. The flat morphology in region A, which is presumed to have cracked due to the penetrator. At the inner diameter (ID), cracking occurred along the bond line and propagated along the base metal toward the outer diameter (OD). This may have been caused by the sound welded middle diameter (Mid) with a narrow width due to the peculiar shape of the welded joint. To improve the flaring ratio, therefore, it is very important to minimize the vulnerability of the ID.

The microstructures of Fig. 5 show two types of defects on the bond line, where one has the habitual morphology of HF-ERW and the other does not. A flat surface partially appeared on the surface, with the large
area and shape shown in Fig. 5a and b. This was caused by the longitudinal defects, penetrator, as shown in Fig. 5c. The irregularly-shaped defects, however, were distributed over a relatively wide area together with austenitic grains as shown in Fig. 5d, e and f. Based on the EDX obtained at points 1, 2 and 3, all of these were oxides containing Mn and/or Si as shown in Fig. 5g, h, and i, respectively. The oxide surrounding the round particles in Fig. 3c had almost the same elemental spectrum as the irregular shaped oxides, as shown in Fig. 3h and i.

Along with these defects, commingled and randomly distributed hot cracking was found, as shown in Fig. 6. Whisker-type oxides, liquid traces and secondary cracks were found in this region. This may have played a major role in the crack initiation sites, because many of these traces were found in the inner diameter. It is possible that this happened under stress conditions due to the adapted internal bead trimming and “springback” phenomenon of the pipe state [38].

3.3. Penetrator formation

Clearly, it is important for weld defects to be prevented in order to improve pipe performances. The penetrator is a major factor in the deterioration of mechanical and corrosion properties [21,22,25,29].

To identify the penetrator components, EPMA elemental mapping was performed along the longitudinal defects that had formed in the bond line. Fig. 7 shows the backscattered diffraction (BSD) image with

![Fig. 5. Microstructure and EDX results for the bond line: (a) SEM image of fractographs of the flat surface caused by continuously arranged globular particles, (b) magnified image of (a), (c) cross-section view of (a), (d) SEM image of the fractured surface caused by irregular shaped particles, (e) magnified image of (d), (f) cross-section view of (d), and EDX results of (g) point 1 of (c), (h) point 2 of (c), and point 3 of (g).](image1)

![Fig. 6. SEM image of fractographs implying hot cracking near the inner diameter surface: (a) low magnification image, (b) secondary crack and (c) liquid trace.](image2)
the elemental distribution of Fe, Mn, Si, Cr and O. The results demonstrate that the round particles mentioned in Section 3.2 had higher manganese and oxygen content, but contained very little Fe, whereas the other surrounding phase had remarkably higher silicon contents and relatively less manganese. Thus, these particles were formed in the liquid phase at high temperature, based on their shape and composition. On the other hand, there are clear distinctions of alloying compositions between the region indicated by the white arrow on the elemental map of Mn and the surroundings. Both provide strong evidence for a different solidification period. The high probability of remaining molten metal made the solidification period longer, because of its high concentration of alloying elements [16].

On the other hand, regardless of oxygen, the Fe-depleted and Mn-segregated zone is partially found at the dendritic boundary of the austenitic region. It is expected that the formation of nano-sized carbides and oxides in Fig. 8 was affected by the segregation of alloying elements, such as carbon and manganese [16,39]. It would appear M$_2$C carbide was formed [40] due to its low alloying elements excepting Mn, given in Table 1. The presence of such dendritic carbides is predicted to cause a weak point in terms of the ductility, even when the oxygen is completely eliminated.

For accurate analysis of the penetrator, its crystal structure was investigated by TEM. The area from which the sample was extracted by FIB was selected in order to collect two types of particles and matrix at once, as shown in Fig. 9a. Just like the SEM specimens, FIB sample was prepared for analysis in the rolling direction, RD. Fig. 9b shows the Pt protective coating layer that is deposited on the region of interest. Electron transparent TEM foil was prepared through ion milling. Fig. 10a and b show the STEM image of the FIB sample with a more highly magnified version in the white dashed box. With the line-scanned elemental distribution indicated by the white dashed line, three elements obviously show fluctuation bordering each of the two interfaces, as shown in Fig. 10c. As compared to the adjacent region, the Si was significantly depleted and the Mn was enriched. This indicates that the large globular

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**Fig. 7.** EPMA maps for elements of Fe, Mn, Si, O and Cr with BSE image around the penetrator in the bond line.

**Fig. 8.** (a) SEM image of the dendritic structure with nano-sized carbide and oxide at the bond line, (b) magnified view of (a).

**Fig. 9.** SEM images showing the lift-out procedure in FIB: (a) The region of interest in order to collect two types of particles and matrix at once and (b) the deposited Pt protective coating layer.
particle had the highest manganese content, while the other had the highest silicon content with a moderate amount of manganese. These results agree with the tendency indicated by the EPMA. Based on the EDX data and corresponding SAED patterns shown in Fig. 10d and e, it has been verified that the penetrator consisted of MnO (Manganosite) with [011] zone axis and Mn$_2$SiO$_4$ (Tephroite) with [001] zone axis. For accurate analysis, more than two SAED patterns obtained from different zones with each phases. Since there was almost no Fe, the Mn–Si–O ternary system can be interpreted considering these oxidation behaviors.

According to the Mn–O–Si$_2$O$_3$ phase diagram [41, 42], at a high manganese concentration, the liquid-state oxide solidified into manganosite ranging from a low of 1315 °C to a high of 1850 °C at the beginning of solidification. Following the initial solidification, eutectic tephroite formed together at a temperature below 1317 °C, which is the eutectic temperature. From these results, the microstructural evidence of globular particles with the surrounding phase suggested that the penetrator was formed in the liquid phase. It is important to explain that those have clearly different solidification periods, as well as to verify what the penetrator consists of. The re-entry of molten metal caused weld defects with high oxygen content and consequently those that were continuously arranged is deteriorate mechanical properties of weldments [23, 25].

In addition, the melting temperature of multi-oxides in a Mn–Si–O system was determined by the ratio of MnO to SiO$_2$. Especially in the HF-ERW process, the ratio was maintained at 1.6:1 in order to keep the molten metal containing oxygen from re-entering according to phase diagram [42]. From the fact that TWIP steels generally have high Mn contents, there needs to be proper oxygen-control and to adjust the ratio importantly.

4. Conclusions

This study focused on applying the HF-ERW process to the seam welding of expandable pipe using TWIP steels. A flaring test was performed in order to measure the circumferential ductility. Both welded and cracked pipe states were investigated in order to determine the effects of defects on the flaring performance. For improvement of the circumferential ductility, bond line discontinuities were characterized. The major findings include:

- Dominant characteristics of HF-ERW, including the metal flow and distinct features at the bond line, were described in TWIP steels. In the bond line, oxide defects existed even when the welding was done in an adjusted gas atmosphere, and dendritic structures were formed because of the high alloysing contents.
- There is a high probability that molten metal will remain because of the high concentration of alloying elements, which would lengthen the solidification period. This caused the molten metal to have a large amount of oxygen for a long time. The EDX and EPMA results showed that irregular-shaped oxides formed besides the penetrator in the bond line.
- The deterioration of the circumferential ductility in a high-Mn TWIP steel pipe was mainly caused by a penetrator that had been formed during welding. Thus, it will be possible to improve the circumferential ductility of the pipe by lowering of both oxygen partial pressure and the ratio of MnO to SiO$_2$.
- Microstructural evidence of the existing theory about the penetrator formation mechanism was presented at two points. First, the TEM analysis proved that the penetrator consisted of round MnO and Mn$_2$SiO$_4$ surrounding MnO. Secondly, the remarkably high Mn-segregated austenitic region suggested that penetrator formed at a different solidification time.

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References


