Fatigue characteristics of small radius pipe fabricated by pipe bending with induction local heating

Y.S. Lee\textsuperscript{a*}, J.S. Lim\textsuperscript{a}, Y.N. Kwon\textsuperscript{a}, Y.H. Moon\textsuperscript{b}

\textsuperscript{a}Korea Institute of Materials Science, Changwon and 641-831, Korea
\textsuperscript{b}Pusan National University, Busan and 609-735, Korea

Abstract

Bending applying local induction heating is an efficient way to produce bended pipes of various radii with lower cost and to provide better quality product. In this process, it is very important to control the thickness of the pipe to ensure its performance. The lower thickness usually turned out in outer section of bended pipe, even though controlling the thickness carefully by reverse moment. As the radius of pipe is smaller, especially, the thickness reduction is larger. The reduced thickness becomes a cause of deterioration of properties and confidence of bended pipe.

To verify confidence of bended pipe, the fatigue properties were investigated for the bended pipes with small radius of the curvature of 1.5 ~ 2.0DR. Two bended sections, which were extrados and intrados region, were compared with as-received section about microstructure, hardness, high cycle fatigue and residual stress. Carbon steel showed better fatigue characteristics at bended section than at as-received pipe. Improvement of fatigue strength resulted from both refinement of ferrite grain size and the achievement of a relatively fine pearlite by both plastic deformation and rapid-heating-cooling during pipe bending applying local induction heating. Hardness increased over 20% and fatigue endurance limits of deformed section were enhanced over 10%.

Keywords: carbon steel, induction heating, residual stress, small bended pipe, fatigue strength;

1. Introduction

Bending applying local induction heating is an efficient way to produce bended pipes of various radii with lower cost and to provide better quality product. It has been used widely in many fields, such as in
the power, transportation and chemical industries and so on, since it was invented by Dai-ichi High Frequency Co. (DHF) of Japan in 1961.

In pipe bending processes, it is very important to control the thickness of the pipe to ensure its performance. Thickness variation is one of the most important design criteria and also quality control variables to ensure mechanical properties of bended pipes. To obtain a required uniform thickness, pipe pushing load is needed to control with reverse moment. Many previous studies were performed to investigate the thickness distribution of pipe by FEM analysis [1-4]. This reverse moment applies compressive force to the pipe. Compressive force improves material properties, thereby change the phase, grain refinement, surface hardening and also compressive residual stress. The lower thickness usually turned out in outer section of bended pipe, even though controlling the thickness carefully by reverse moment. As the radius of pipe is smaller, especially, the thickness reduction is larger. The reduced thickness becomes a cause of deterioration of properties and confidence of bended pipe.

To verify confidence of bended pipe, the fatigue properties were investigated for the bended pipes with small radius of the curvature of 1.5 ~ 2.0DR. Two bended sections, which were extrados and intrados region, were compared with as-received section about high cycle fatigue, microstructure, hardness and residual stress. Fatigue properties of small radius bended pipe were investigated by thickness variations, metallurgical characteristics and residual stress at extrados and intrados.

2. Experimental

A pipe bending process is composed of local induction heating of pipe, bending by radial arm, rapid cooling by water cooling device and continuous feeding by pusher and guide roller, as shown in Fig. 1. Pipe is heated up 1,100°C by induction local heating. Bended pipe is usually subjected to tension stress and the wall of pipe get thin on extrados of bended pipe. On the other hand, it is subjected to compressive stress and the wall of pipe become thicker on intrados of pipe.

The dimensions of pipe are as follows; the diameter is 170mm and thickness is 12mm. As a same tendency, the thickness got thinner on extrados of bended pipe, however, the thinning ratio (deformed thickness/original thickness) could be sustained under 5% by the parameter control. Material of pipe is a low carbon steel (SA106GrB) and the chemical compositions is shown in Table 1.

<table>
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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
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<th>Mo</th>
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<td>0.4</td>
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</table>

Table 1. Chemical composition of SA106GrB

![Fig. 1. Schematic illustration of pipe bending process with induction local heating bending and prototype of bended pipe](image-url)
Two bended sections, which were extrados and intrados region, were compared with as-received section about high cycle fatigue, microstructure, hardness and residual stress, as shown in Fig. 2. Microstructures were evaluated by optical microscope and Vickers hardness tester was used to measure the hardness.

Residual stresses were measured by destructive testing method. Since non-destructive testing method can be measured only surface of pipe, hole drilling test also is used to evaluate the residual stress along the depth of pipe. Drilling method is based on the ASTM E837-08. The drilling depth is located with 0.1mm distance up to 1.6mm depth from the surface. Three strain gages (Vishay co., USA) were attached on surface of pipe along the circumferential direction, as shown in Fig. 2.

![figure](image)

Fig. 2. Test piece positions evaluating metallurgical and mechanical properties (a) raw material, (b) intrados, (c) extrados

### 3. Results and Discussion

For the S-N fatigue test, a magnetic resonance fatigue testing machine was used on operating condition that frequency was 80 Hz and R ratio was positive 0.01. Fig. 3 shows (a) the photo showing magnetic resonance fatigue testing machine and (b) the hour-glass type fatigue specimen, respectively, used in this study. All specimens were machined into longitudinal direction. The specimens on bended pipe were machined after flattening at 170 ~ 200°C.

Fatigue strengths of deformed metal at bended positions, such as extrados and intrados, are enhanced about 10%. Fig. 4 represents the S-N curves of raw material, intrados and extrados. Endurance limit of fatigue strength increased up to 500MPa on intrados, while the values of extrados and raw material are 450MPa and 425MPa, respectively.

Fig. 5 shows microstructure of raw material that is all the ferrite-pearlite lamellar structure at three positions, which are outside, center and inside. Vickers hardness is the range of Hv140 ~ 180. Ferrite grain is refined and pearlite is also refined, as shown in Fig. 6 after quenching. Fig.6(a) and Fig.6(b) show the microstructures of extrados and intrados, respectively.
Microstructure of extrados is refined relatively more than that of intrados because extrados is cooled rapidly after bending. Volume fraction of pearlite on outside of extrados and intrados increased and then hardness also increased. The hardness of extrados and intrados increased, therefore, Vickers hardness of intrados is Hv220 ~ 260 and the value of extrados is up to Hv280, as shown in Fig. 7(a). These grain refinement and hardness changes caused microstructural changes by the heating, plastic deformation and cooling. All residual stress of specimens has a transition thickness from the surface into inside of pipe. Fig. 7(b) shows maximum stress distribution along the thickness and represents transition thickness well. The transition thickness of raw material, intrados and extrados is 0.5, 0.5 and 0.3mm from the surface, respectively.

The patterns and also values of residual stresses at each position were almost same, therefore, residual stress did not affect on fatigue strength in this case. The enhancement of fatigue strength is due to the microstructural changes during pipe bending process with local induction heating.
Three important strength mechanisms of plain carbon ferrite-pearlite steel are solid solution hardening, grain size and dispersion strengthening from lamellar pearlite. [5,6] In this study, improvement of fatigue strength resulted from both refinement of ferrite grain size and the achievement of a relatively fine pearlite, based on the results of hardness, microstructure and fatigue strength.

Fig. 5 Microstructures of raw material, SA106 GrB

Fig.6 Microstructures at each position of bended pipe (a) extrados, (b) intrados
Fig. 7 Hardness and residual stress distribution of raw material and deformed section; (a) hardness, (b) residual stress

4. Conclusion

Carbon steel showed better fatigue characteristics at bended section than at as-received pipe. Improvement of fatigue strength resulted from both refinement of ferrite grain size and the achievement of a relatively fine pearlite by both plastic deformation and rapid-heating-cooling during pipe bending applying local induction heating. Hardness increased over 20% and fatigue endurance limits of deformed section were enhanced over 10%.

References