Evaluation of Tensile Properties for TP316 Stainless Steel Pipe Bends Manufactured by High-Frequency Induction Heating Process

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1. Introduction

Pipe bending by high-frequency induction heating is one of the hot bending processes. This technique directly makes pipe bends by bending a portion of straight pipe, so it eliminates welds between bend and straight pipe and produces bend with arbitrary angle and radius [1-3]. Because of these advantages, this technique is commonly used to manufacture pipe bends for power plants and shipbuilding plants [1-3]. This type of pipe bends are also partly used in non-safety piping systems of nuclear power plants (NPPs). Recently, it is attempted to apply such pipe bends to the safety related piping systems in NPPs.

In this bending process, however, a narrow region of pipe is heated above annealing temperature for a few minutes and rapidly cooled. Also, the material undergoes extensive plastic deformation during bending; the extrados is strained resulting in a thinning of wall thickness and the intrados is compressed resulting in an increased wall thickness. Thus, it is expected that the mechanical properties of the pipe bends are different from those of mother pipe (straight pipe). In addition, the spatial variation of mechanical properties is significant compared to the conventional pipe bends. Therefore, it is important to investigate the mechanical properties of pipe bends manufactured by high-frequency induction heating process and the distribution of mechanical properties within the bends. When the pipe bends are used for safety related piping systems in NPPs, in particular, the investigation is more important because most of them are designed considering leak-before-break (LBB) which requires actual mechanical properties of pipe bend [4]. Therefore, this study conducted tensile tests using specimens machined from various locations within pipe bend bent by high-frequency induction heating at ambient and operating temperature of NPPs. From the results, the change of tensile properties by bending and the spatial variation of tensile properties within the pipe bend were investigated.

2. Material and Experimental Procedures

2.1 Material and specimens

The specimens were machined from the pipe bend made by bending a straight pipe of SA312 TP316 stainless steel with dimension of 12-inch, Sch. 160. Bend radius and angle of pipe bend are 1.8 times of pipe diameter (D) and 45-degree, respectively. The straight pipe was annealed at 1060°C for 10min. followed by quenching. Table 1 lists the chemical composition of the straight pipe. Tensile specimens were machined from various locations in the pipe bend; extrados, intrados, and crown at center and transition regions. At each location, both directions (L- & T-direction) were considered. Fig. 1 illustrates the locations of specimen in the pipe bend. To obtain reference data, the specimens were also machined from straight pipe. A round-bar type specimen with diameter of 6mm and gage length of 25mm, which complies with ASTM E8/8M-09 standard [5], was used in the tests.

Table 1 Chemical composition of SA312 TP316

C	Si	Mn	P	S	Cr	Ni	Mo
0.02	0.039	1.31	0.009	0.000	16.4	11.2	1.05

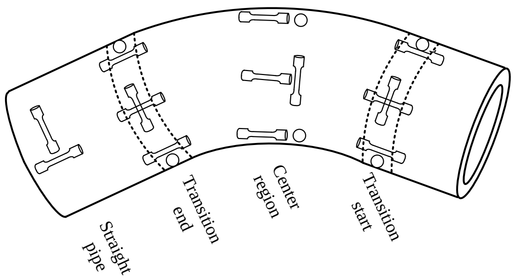

Fig. 1 Location of tensile specimens in the pipe bend

2.2 Test condition and procedures

Tensile tests were conducted at ambient and operating temperature of NPPs (316°C) under a displacement rate of 1.0mm/min which corresponds to strain rate $\dot{\varepsilon} = 5.208 \times 10^{-4} / s$. In the tests, a motor-driven universal test machine with load-cell of 50kN capacity was used to apply tensile load, and the strain of specimen was measured by high temperature extensometer with gage length of 25mm. At ambient temperature single specimen was tested for each condition, but at operating temperature three specimens were tested for each condition.

3. Results and Discussion

Engineering stress-strain curves for pipe bend were obtained from the tests and compared with those of straight pipe. It showed that the strength of pipe bend was higher than that of straight pipe and the ductility was lower than that of straight pipe regardless of test temperature and direction of specimen. That is, the strength was increased and the ductility was decreased by high-frequency induction bending.

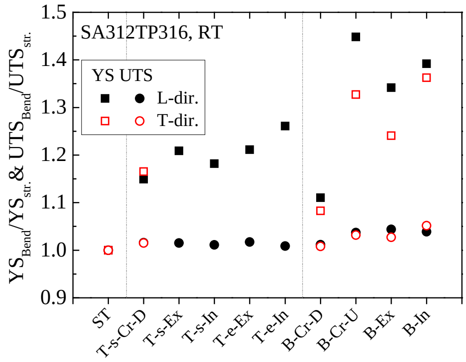

Fig. 2 Distributions of yield and tensile stresses of pipe bend at ambient temperature

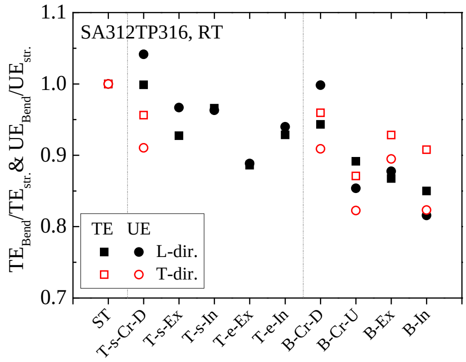

Fig. 3 Distributions of uniform and total elongations of pipe bend at ambient temperature

To quantitatively investigate tensile properties of pipe bend, yield and tensile stresses and total and uniform elongations were evaluated and compared in accordance with location of specimen in the pipe bend. Fig. 2 presents the yield and tensile stresses of pipe bend at ambient temperature normalized with respect to those of straight pipe as function of location. It showed that the yield and tensile stresses of pipe bend are higher than those of straight pipe. In particular, an increase in yield stress rather than tensile stress was considerable. An increase in tensile stress in pipe bend was less than 5% compared to straight pipe. Within pipe bend region, the yield stress was much higher at center of bend (B-) than transition regions (T-). In the center of pipe bend, the highest yield stress appeared at intrados (B-In) and the lowest appeared at a side of crown (B-Cr-D). A significant difference between yield stresses at both sides of crown can be seen, but it is associated with different circumferential location of specimen. By comparing with direction of specimen, an increase in yield stress at bend region was slightly higher for L-direction than C-direction.

Fig. 3 shows uniform and total elongations of pipe bend normalized with respect to those of straight pipe. Uniform and total elongations at pipe bend were reduced compared to straight pipe. The reduction of elongations was more significant at center of bend than at transitions. Within center of bend, intrados showed lowest elongations and a side of crown (B-Cr-D) showed highest elongations. By comparing with specimen direction, a decrease in elongations was slightly higher for L-direction than C-direction. These variations of elongations agree well with spatial variation of strength. These characteristics of tensile properties of pipe bend were also observed from the results at 316^{o}C. That is, the yield and tensile stresses were increased and uniform and total elongations were decreased by high-frequency induction bending. In particular, the yield stress at intrados region of bend was significantly increased.

4. Conclusions

1) At both ambient and 316^{o}C, the strengths and ductility of pipe bend were increased and decreased compared to straight pipe, respectively. In particular, an increase in yield strength was apparent.
2) Within bend region, increase in strength and decrease in ductility were more significant at center of pipe bend than at transitions of bend.
3) At center of pipe bend, the variations of tensile properties were more significant at intrados region of pipe bend than at extrados region.

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