# Finite Element Analysis of Wall Thinning in Induction Bending Based on a Coupled Electromagnetic-Thermal-Mechanical Model

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## 1. Introduction

Induction bending is a pipe-forming process in which a pipe is locally heated by induction and pushed forward to produce a bent pipe. It has been widely used in the shipbuilding and plant industries due to its advantages in improving productivity and eliminating circumferential welds between straight and curved pipe sections. The applicability of this process to small modular reactors (SMRs), which require complex piping layouts in limited spaces, is also being investigated. However, during induction bending, the wall thickness at the pipe extrados decreases as a result of the axial tensile stress concentrated within the softened band. For the structural integrity of the pipe, the wall thickness reduction rate must not exceed the allowable limit of 12.5% [1]. To satisfy this requirement, a reverse moment applied opposite to the bending direction has been used, as it lowers the axial tensile stress at the extrados and suppresses wall thickness reduction [2].

In previous study [2], the heat source was not obtained from the electromagnetic field, so the coil design, frequency, and input power could not be treated as design variables. In this study, therefore, the bending process was simulated using a heat source obtained from an electromagnetic-thermal analysis, and the effects of the process parameters on wall thickness reduction were investigated through finite element analysis (FEA) to evaluate the sensitivity of each parameter.

## 2. Process Principle

Figure 1 illustrates the principle of the induction bending process. The bending machine consists of a pusher, a heating coil, a bending arm with a clamp, a cooling system, and guide rollers. The induction bending process begins with preheating the stationary pipe using the heating coil. After reaching the target temperature, the pipe is pushed forward through the coil, and the heated band is quenched by a water spray from the cooling system. The pipe is simultaneously guided by the bending arm until the targeted bending angle and bend radius are achieved. The bending process can result in geometric imperfections, including wall thinning and cross-sectional ovality.

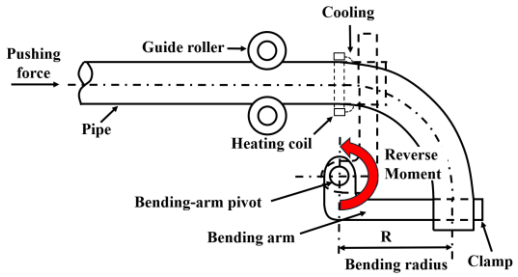



Fig. 1. Outline of pipe bending using induction heating.

## 3. Finite Element Analysis of Induction Bending

### *3.1 Material Properties and Analysis Conditions*

An 8″ NPS (Nominal Pipe Size) SA-106 Grade B pipe was used in this study, and its temperature-dependent properties are presented in Fig. 2 [3,4]. The process parameters considered for the sensitivity analysis are summarized in Table I.

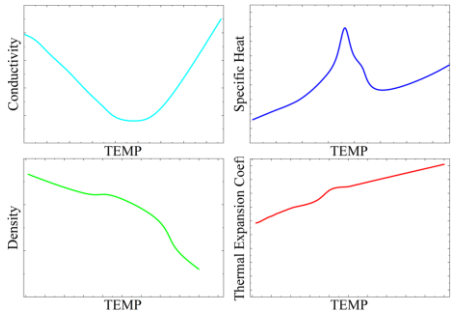



Fig. 2. Temperature-dependent properties of SA-106 Grade B.

Table I: Process parameters

| | Level | Unit |
|---|---|---|
| Feeding velocity | 0.8v, v, 1.2v | mm/min |
| Reverse moment | 0, M | N·m |
| Heat input | 0.6Q, 0.8Q, Q | W/m$^3$ |

### *3.2 Electromagnetic-Thermal Coupled Analysis*

Induction heating was modeled as a fully coupled electromagnetic-thermal analysis using ABAQUS [5],

as shown in Fig. 3. The rate of Joule heat dissipation (EMJH) computed in the electromagnetic analysis was transferred to the heat transfer analysis as a concentrated heat flux (CFLUX). In this analysis, the two analyses proceeded while exchanging the computed temperature field at every increment. The analysis model was validated by comparing the computed temperature histories with the experimental results, and the two showed good agreement, as presented in Figs. 4 and 5.

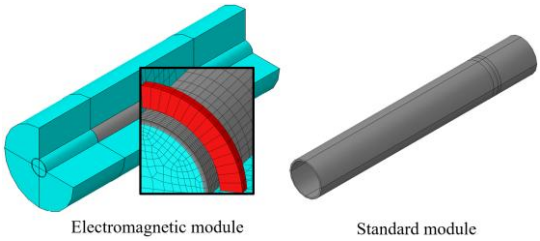



Fig. 3. Electromagnetic-thermal coupled model.

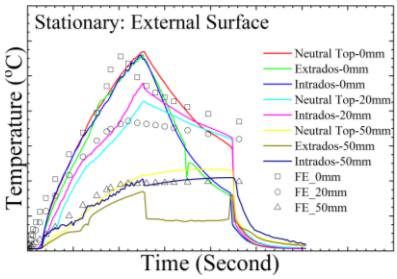



Fig. 4. Comparison of the temperature histories obtained from the analysis and experiment under stationary heating,

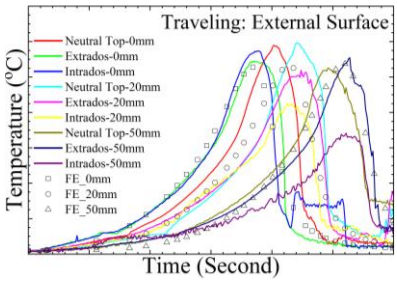



Fig. 5. Comparison of the temperature histories obtained from the analysis and experiment under traveling heating.

### *3.3 Thermo-Mechanical Coupled Analysis*

Induction bending was modeled as a coupled thermo-mechanical analysis. As shown in Fig. 6, the clamped pipe end was rotated about the bending arm pivot to simulate the bending.

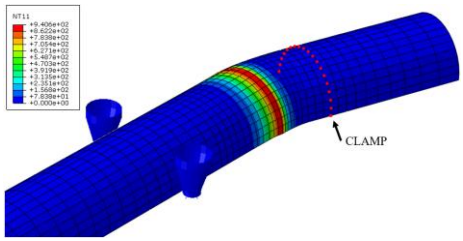



Fig. 6. Thermo-mechanical coupled model.

## 4. Results and Discussion

When the reverse moment was applied, the wall thickness reduction rate was lower than 12.5%, as shown in Fig. 7. Among the process parameters examined, the wall thickness reduction rate was most sensitive to the reverse moment, followed by the heat input and the feeding velocity. The reduction rate was highest at the 60° section of the bend, where the accumulated axial tensile stress reached its maximum. In addition, a low feeding velocity or high heat input overheated the locally heated region, causing wrinkling at the intrados.

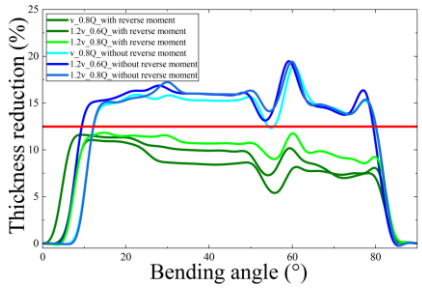



Fig. 7. Effect of the reverse moment on wall thickness reduction.

## 5. Conclusions

The reverse moment suppressed the axial tensile stress at the extrados. Without it, the wall thickness reduction rate exceeded the allowable limit of 12.5%. The reduction rate was most sensitive to the reverse moment, followed by the heat input and the feeding velocity, and was highest at the 60° section of the bend.

## ACKNOWLEDGEMENT

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