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Increasing bending angle in thick-walled pipes with wide heating

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Abstract. The spot heating of a metal part leads to many small deformations. The applications of this method are straightening the bridge parts, turbo-machinery shafts, and so forth. The movement of the heat source on a given path (line heating) leads to an increase in the deformation and the possibility of creating complex bends. However, it is complicated to predict and control the path and velocity of the heat source as well as determining the heat intensity. In the pipes, this method requires simultaneous control over the two torches on both sides of the pipe. The present study aims at investigating the mechanism of deformation and increasing the bending angle in thick pipes by means of a simple heating method. At first, the maximum bending in heating a large circular zone (entitled "wide heating") is obtained by simulating the process using finite element method and optimizing it applying the genetic aggregation algorithm. Then, a new method for simultaneous heating within two zones is introduced. The interaction between two zones leads to the development of the shortening mechanism in the pipe wall and a significant increase in the bending angle. In this method, there is no need to move the torch where the temperature is controlled more accurately. To evaluate the finite element model, several pipe heating tests are performed with their results being agreed well with the simulation results.

1 Introduction

Correcting the shape of the pipes, axes, and bridges is a practical application in various industries. Welding, collision, work stress, etc. lead to distortion of parts. Also, during piping operations, the precise adjustment of the pipes at the junction with one another encounters problems leading to a need for correction of the direction of pipes. For straightening pipes and shafts, various methods are used, namely cold and hot bending, blasting, heat treatment, spot heating, line heating, etc.

In a spot heating procedure, a small area of the surface of a metal part is rapidly heated by a heat source (usually a gas torch). To avoid any contact with gas, the surrounding areas are covered with insulation layers. The heated zone expands and is subjected to the pressure of the surrounding cold zone. Increasing the temperature leads to an increase in compressive stress and a reduction in the yield stress of the heated zone, a slight bulging, plastic strain, and ultimately reducing the length of the heated zone after cooling and deformation of the piece [1,2]. Li and Yao [3] examined various mechanisms of thin pipe deformation by heating. This method is simple and inexpensive when using a gas torch. Also, its equipment is portable.

One of the limitations of spot heating is the very low deformation and the impossibility of re-heating a zone to increase deformations [4,5]. To increase the bending angle (average transverse displacement of the pipe end per unit length), it is possible to apply pre-stress to the heating zone [6,7]. But this requires the use of a suitable tool for applying the necessary initial bending to the piece which is limited to the bending equipment and yield limit of the part. Also, controlling the surface temperature is difficult during heating. The simulation of the process by FEM can predict deformations. But it requires to determine the amount of heat applied by the gas torch and the material properties variation over temperature.

In our previous studies [1,8] the pipe bending angle was increased by optimizing the hot spot parameters. CFD analysis of flame flow is carried out to determine the heat flux distribution over the pipe surface. Furthermore, the appropriate distance for combining the hot spots was also obtained. The maximum bending of $0.149\,\mathrm{mm/m}$ was achieved which is more than three times the bending was provided by conventional spot heating [2,4]. To evaluate the results, the Spot Heating test was performed.

Another method for heat bending is to move the heat source along certain paths, which is called "line heating". This method requires the identification of suitable paths and control over the torch movement. The prediction of deformation is complex in this method. Several references

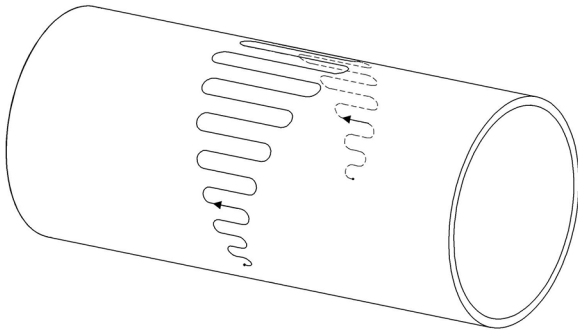* e-mail: e_moussavi@sbu.ac.ir

Fig. 1. Holt method for pipe bending [4].

have investigated the path determination algorithms in the plates as well as the relationship between plate deformation and process parameters [9–12]. Even recently, an automatic plate bending equipment has been made that can calculate the path and heating parameters needed to create a certain shape [10]. The line heating method faces more operating problems than spot heating due to the need to control the speed, path, and heat intensity of the torch.

The use of line heating along longitudinal reciprocating paths in pipes (Holt method − Fig. 1) is an old method for pipe bending. This method results in a significant increase in the bending angle and reduction of tensile stresses in the heating zone relative to spot heating [2,4]. The method requires the movement of two torches with the same heat intensity and speed on the pipe sides, which is hard to be implemented.

Gatto et al. [4] mentioned a report that the use of line heating for bending A36 beams led to lower tensile stresses than conventional rolled products. According to the report, bending shafts and pipes by line heating method is more stable than other bending methods (cold bending, etc.).

Avent [6] examined the line heating method for straightening bridges in detail. He investigated heating paths to create suitable deformations, temperature limitations, ductility changes in steel, and so forth. The results were based only on multiple tests, and there was no modeling. Gatto et al. [4] conducted several tests to investigate pipe bending by spot heating and Holt's method. However, their results did not led to a model for predicting the behavior of pipes or achieving maximum bending. They applied the spot heating by a torch in a small area (about 20 mm radius) of pipes of 150 mm diameter and 12.5 mm thickness. Therefore, bending angles (transverse displacement of pipe end per unit length) of the order of one-hundredths millimeters per one meter of pipe length were created. Using the Holt method, they also increased the bending angle to 2.5 mm/m in pipes with a diameter of 200 and a thickness of 7.9 mm. According to their results, the repetition of line heating in one area led to an increase in bending. But it is worth noting that Connor et al. [13] and Avent et al. [6,14] investigated the changes in fatigue and fracture characteristics of materials during the elimination of bridges distortion by the line heating method. Their results showed a significant reduction in the yield stress and toughness of the steel by heating the same zone more than three times.

The simulation of the process by Finite Element Method was carried out in laser heating of the thin-walled pipes with thicknesses up to 2 mm (due to the limited power and cost of laser equipment) [15–17]. The simulation of plate forming by the line heating was carried out in numerous studies [11,18,19]. But in the investigated references, the use of line heating method in straightening of the thick pipes was limited to tests [2,4] and the simulation of the forming process was not performed.

To avoid the metallurgical phase change of the heated zone, the surface temperature should be controlled. The maximum temperature in Gatto et al. [4] and Avent [6] tests was 650 °C, because of temperature control problems. A recent study has indicated that if the temperature increases to 760 °C in A36 carbon steel, there is no significant change in material properties compared to the case that the temperature is increased up to 650 °C [7].

In the present study, wide heating (spot heating by a large spot diameter) of thick pipes is introduced and its deformation mechanism is investigated. The pipe bending angle increases by optimizing the process parameters using numerical simulation. Then a new method is developed for simultaneous heating within two zones. Several pipe heating tests are performed to assess the numerical method.

2 Numerical modeling

The pipe heating and bending process is modeled via FEM to investigate the deformation mechanism, optimize the bending angle, and examine the new heating method. All of the analyses are performed using the ANSYS FE code.

2.1 Simulation setup and optimization method

The pipe used for the analysis and tests has an inner diameter of 203.2 mm and a thickness of 8.18 mm. Moreover, the effect of diameter and thickness variations on the results is discussed. Figure 2 shows a half model of the pipe (due to its symmetry) with loading and boundary conditions in different heating methods.

The effect of surrounding air is modeled as natural convection. The studies showed that the results were not sensitive to the exact amount of convection coefficients. The thermal analysis is nonlinear because of the dependence of the material properties on the temperature. Furthermore, the structural analysis is nonlinear due to the plasticity. Thus, the Full Newton-Raphson method is used to reach a better convergence of the FEM model.

The presence of two field variables, displacement and temperature, leads the structural and thermal equations to be coupled through the thermal expansion coefficient and also results in the temperature dependency of material properties. The heat produced by the plastic work is very small and can be ignored. Also, the structure deformation due to heating is very small and does not affect thermal loads. So, the problem is "weak coupled" and it is possible to solve the coupled thermal-structural problem sequentially (aka load vector method). Therefore, thermal analysis is first performed and then the temperature distribution is transferred to the structural analysis as a load vector.
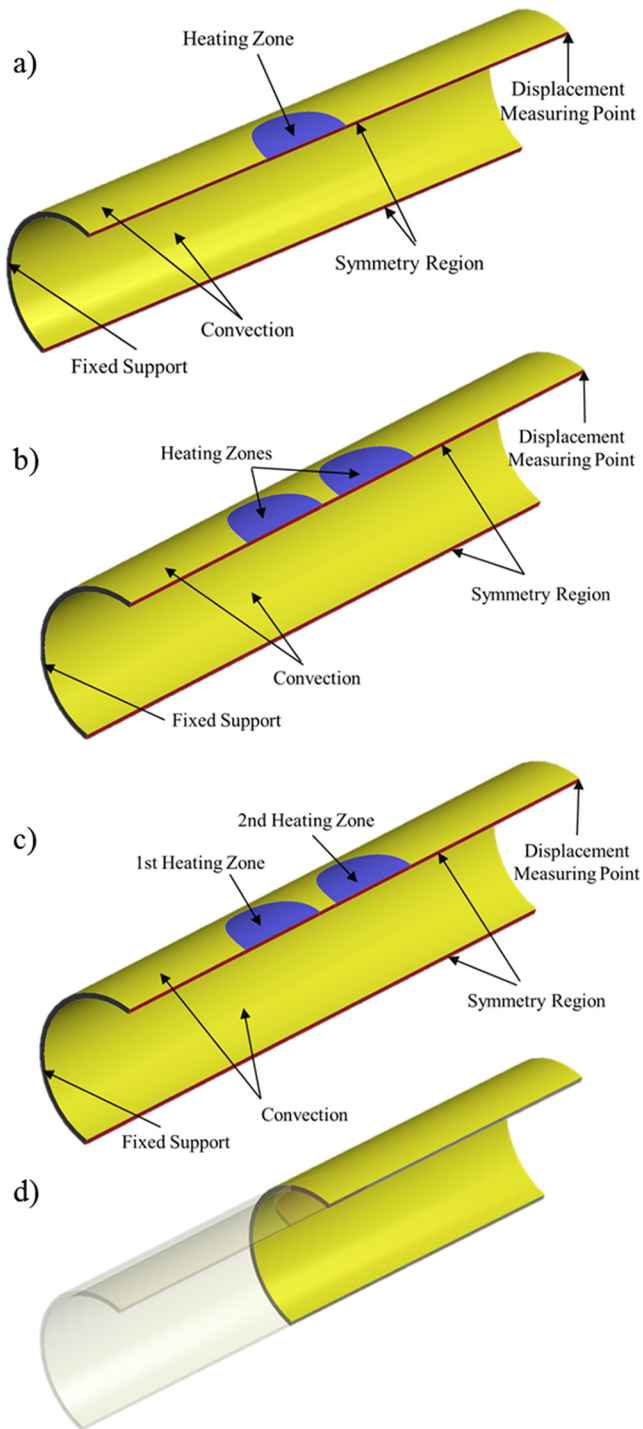
Fig. 2. Pipe model. (a) Single zone heating, (b) simultaneous heating, (c) non-simultaneous heating, (d) a quarter part to show results.

Temperature control is more accurate in this study (4). So the maximum temperature is considered 700 °C as it is higher than Gatto et al. [4] and Avent [6] tests and lower than the metallurgical phase change of carbon steels (AC1 temperature, 723 °C). Thermal analysis is carried out in two steps, heating and cooling. The heat flux is applied in the first stage and removed in the second one. The FEM codes are set such that, after reaching the surface

temperature of 700 °C, the heating is stopped and the cooling is started. Thus, the heating time is incorporated in the problem in the form of the maximum temperature. This method avoids the time parameter direct entry into the problem and also simplifies interpreting the results.

Using the response surface method, the optimization is carried out by applying the genetic aggregation method to maximize pipe bending angle.

2.2 Heat flux distribution

In spot heating and line heating, the heat source has a small radius (for example, an effective radius of 20 mm in Clausen study [11]) and Gaussian distribution is used to model the heat source [11,20]. Although modeling the flame flow (as an impinging jet) using CFD represents a different heat distribution [21–23], the simulation results indicate that this issue does not significantly affect the deformations in small heating radii. Some studies used prescribed temperature distributions for simplicity [19].

In our previous researches [1,8], the spot heating of a pipe was optimized using the Gaussian heat distribution of the torch to increase bending. The parametric study showed that increasing the heating zone radius and the maximum heat intensity, first, led to an increase in pipe bending angle and then a decrease. In the optimum effective radius of heating, changes in the deformation mechanism lead to a significant increase in bending compared to the conventional methods. In the large heating radii (relative to the pipe diameter), the heat flux distribution will not be Gaussian (the surface curvature will change the heat distribution). However, using a large heating torch and insulating the surrounding area provide a fairly uniform heat distribution. Therefore, in this study, uniform thermal flux is applied to a circular zone with a large diameter, entitled "wide heating" (see Fig. 2a).

2.3 Material properties

Measuring the mechanical properties of pipes has been discussed in some references [24,25]. DIC method is one of the advanced methods to measure the mechanical properties of materials [26–28].

In this research, a SA-106 carbon steel seamless pipe, with 0.192% carbon verified by a Quantometer test, was used for tests and analyses. The tension test was carried out over four samples from the pipe at ambient temperature (according to ASTM E 8M) where the average young modulus and yield stress, and tangent modulus were obtained of 210 GPa, 295 MPa, and 4900 MPa, respectively (Fig. 3).

Varma [7] described general relations for modulus of elasticity, tangent modulus, and yield stress of low carbon steels in terms of temperature. Incorporating the yield stress and tangent modulus obtained from the tension test in these relations, the necessary values for the analysis were obtained. Variations of density, coefficient of thermal expansion, specific heat capacity, etc. were derived from Clausen research [18]. Avent et al. [14] also employed fairly similar properties. The structural properties of the steel are shown in Figure 4.
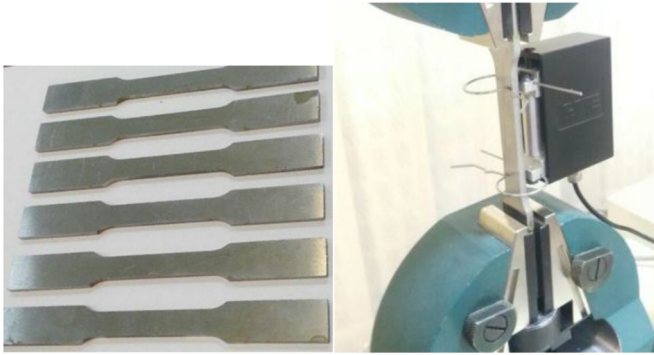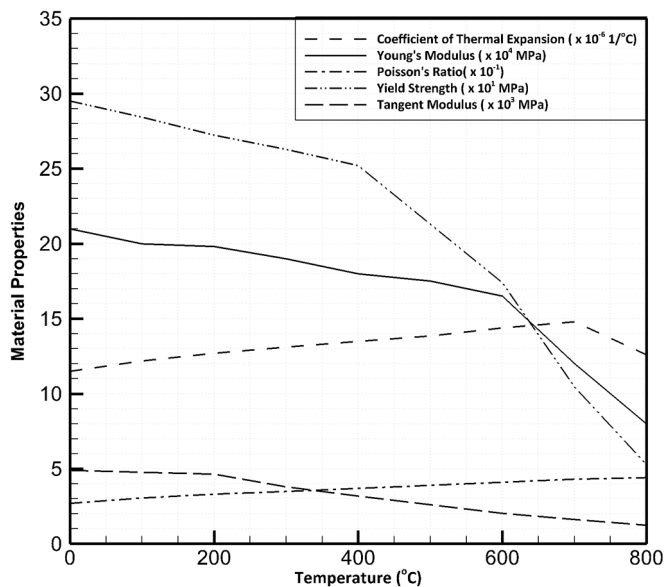
Fig. 3. Tension test specimens.

Fig. 4. Structural properties of the steel.

Von Mises yield criteria and Kinematic Hardening is used in the current study.

2.4 Meshing and mesh independency

A view of the pipe half model mesh with quadratic solid elements is shown in Figure 5.

The results of the finite element analysis should be independent of the element size. Having a fine mesh, the gradient of quantities in different directions (especially through the thickness) will be captured properly. To examine how the element size affects the results, the longitudinal residual stress distribution was investigated over a longitudinal path. The path and the results are shown in Figure 6. It is worth noting that the path is located on the outer edge of the pipe cross-section. The longitudinal residual stress in the heating zone is tensile in the inner edge and compressive in the outer edge. The two parameters TH and LE are number of elements through thickness and length of elements in the radial direction of the heating zone, respectively. As the elements become smaller, the curves fit in after the initial change. As it can be observed, it is sufficient to apply four elements through the thickness with a length of 5 mm at the heating face to
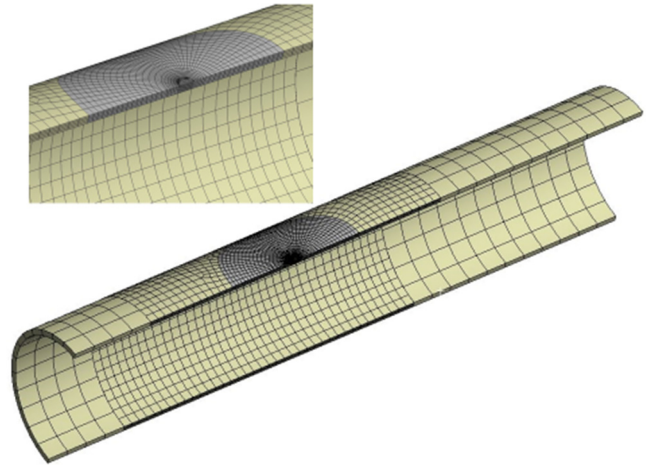

Fig. 5. Half model mesh (in the wide heating of single zone).
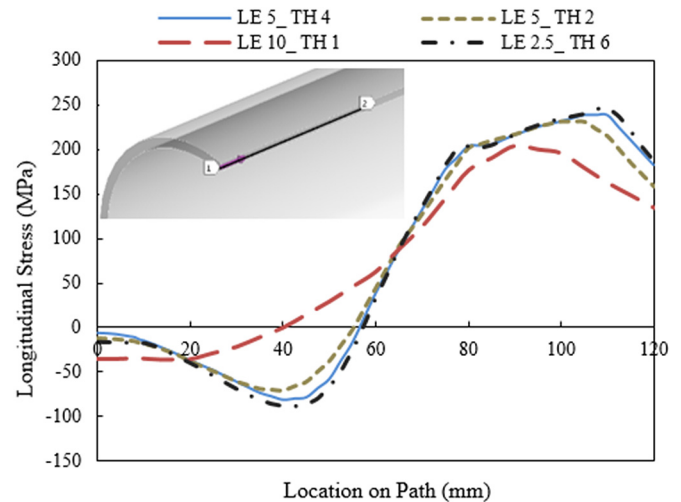

Fig. 6. Longitudinal residual stress variations along the longitudinal path, TH: number of elements through the thickness, LE: element size at the heating face (mm).

meet an accurate response by FEM. The same result was obtained for other components of stress along the longitudinal and tangential paths.

3 Numerical model results

In what follows, the results obtained from numerical model are represented and deformation mechanisms are discussed in detail. The quarter view of the pipe, shown in Figure 2d, is used to illustrate the results in the following figures.

3.1 Wide heating of single zone

The heating zone radius and the applied heat flux intensity are assumed as input parameters for optimization of bending angle in wide heating of single zone (see Fig. 2a). As it was already stated, heating is applied right before the maximum temperature of 700 °C. The response surface for a pipe diameter of 203.2 mm and a thickness of 8.18 mm is depicted in Figure 7. As can be seen, by increasing the
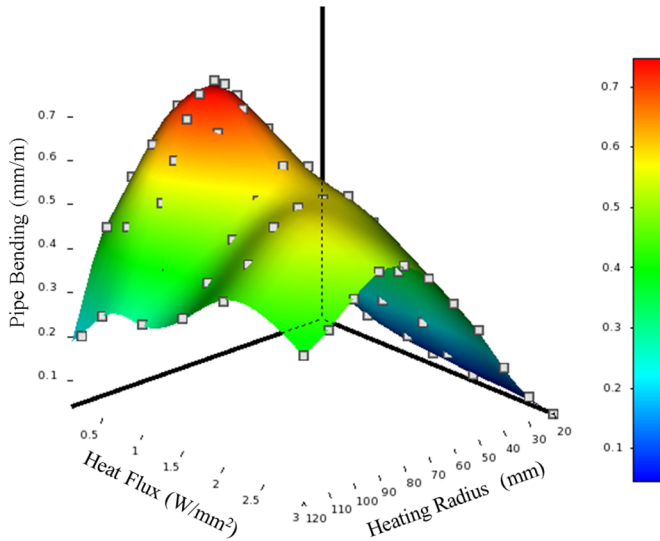
Fig. 7. Pipe bending angle variations (mm/m), pipe diameter: 203.2 mm, thickness: 8.18 mm.

radius once the heat intensity is constant, the displacement increases at the beginning and decreases subsequently. The maximum bending of 0.756 mm/m is obtained at a heating radius of 84 mm and intensity of 0.757 W/mm². This value is several times the bending yielded within the conventional spot heating (0.01–0.04 mm/m) and about 30% of that obtained by the Holt method (Gatto et al. research [4]). Moreover, it is more than twice that obtained by the "optimized spot heating" [8]. This increase reflects the significant effect of uniform heating on a large area and insulation of the surrounding surfaces.

To study the effect of pipe diameter and thickness on the maximum bending angle, a similar process (FE analysis and optimization) was performed and the optimum values of bending angle, heating radius, and heat flux were determined (Tab. 1). As can be seen, in each diameter, the heat flux intensity increases by increasing the thickness.

3.2 Deformation mechanism in the wide heating

As stated in the introduction, different studies discussed the deformation of thin pipes (a thickness ranging from 0.1 mm to a maximum of 2 mm) and plates by laser heating. They proposed three mechanisms, namely thermal gradient mechanisms (TGM), shortening (aka upsetting), and local buckling [3,29]. TGM mechanism was created in the shaft straitening [4] while shortening mechanism was used in the Laser bending of thin pipes [29,30]. However, the heating of the thicker pipes was not discussed. In thick pipes, a cheaper heat source such as a torch is used since the heating zone should have a much larger radius than the conventional lasers.

In small heating radii, since small areas around heating zone are merely placed under stress, the resistant zone, the cold zone subjected to the significant stress caused by the expansion of the hot zone, will be small. However, when the radius of the heating zone is comparable to the pipe diameter in thick pipes, the resistant zone extends over the entire pipe section. Therefore, the flexural strength of

the pipe highly matters, changing the deformation mechanism in the heating process of thick pipes. Figure 8 demonstrates a schematic view of heated and resistant zones in a pipe with different heating radii.

To investigate the deformation mechanism in the concerned pipe, three heating cases were selected from Figure 7 along with one extra case to generate a TGM (Tab. 2). In case 1, the heating radius is very small and the heat flux is very high. In cases 2, 3 and 4, the radius of the heating zone is lower, equal or higher than the optimal radius, and the heat flux is optimal.

The pipe temperature increase through the thickness depends on the radius, intensity, and duration of the applied heat flux. If severe heat is applied in a small area, relative to the thickness and diameter of the pipe, the temperature will quickly reach the permitted limit where the heating stops. Therefore, only the upper part of the thickness expands and undergoes plastic strain under the pressure of the surrounding area with a reduction in length. The pipe first bends downwards and then upward after cooling down. This type of heating occurring in case 1 yields a thermal gradient mechanism (TGM) and reverse bending (relative to the heating direction). In this case, the local bending (bulging) of the pipe is high in the heating zone and its shortening is low, leading the overall bending of the pipe to be drastically low. Figure 9a shows the residual equivalent plastic strain distribution in this mechanism. Also, as shown in Figure 7, small bending is created by small radius and high heat intensity.

If the heat flux intensity decreases while its radius increases or a pipe with higher thermal diffusivity coefficient is used, almost all the thickness is sufficiently heated and expanded. Therefore, the heated area is squeezed, undergoes compressive plastic strain, and is shortened under the pressure of the cold surrounding area. This kind of heating occurring in cases 2 and 3 bears a shortening mechanism in the heating zone and considerable bending of the pipe. The larger the heating area is, the larger the plastic area and the shorter the heating area would be. However, increasing the heating radius will result in the reduction of the resistant area in the pipe section. So the tensile yielding initiates within the resistant section. Therefore, as shown in Figure 7, at a certain heat flux intensity, as the heating radius increases, the bending is first maximized and then decreases. Figure 9b and c shows the distribution of residual plastic strain in cases 2 and 3, respectively. Here, the plastic zone is extended compared to case 1.

With the excessive increase in the heating zone radius in case 4, the resistant area of the pipe becomes smaller and undergoes tensile plastic strain within a large area. Therefore, the compressive stress acted on the heated zone decreases and consequently the compressive plastic strain decreases as well. Thus the final bending of the pipe is reduced. Figure 9d depicts the residual plastic strain distribution in this case. In Figure 7, when the radius of the heating zone is larger than the optimal radius, the pipe bending angle decreases.
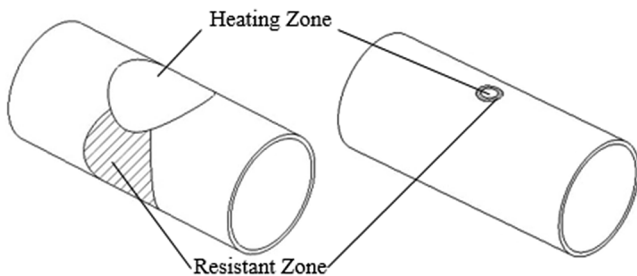
Having a closer look at the pipe deformation mechanisms, Figure 10 illustrates the longitudinal plastic strain (ε_l) along the circumferential path (average values through

Table 1. Maximum bending of different pipes.

Pipe diameter (mm)	Thickness (mm)	Optimum radius of heating zone (mm)	Optimum heat flux (W/mm^2)	Optimum bending (mm/m)
152.4	4	60	1.50	0.8
	8.18	60	1.00	0.736
203.2	4	75	1.02	0.656
	8.18	84	0.76	0.756
	16	96	0.61	0.688
254	4	89	0.81	0.44
	8.18	100	0.60	0.68
	16	105	0.57	0.66

Table 2. Selected cases to discuss on deformation mechanism.

Case number	Heating radius (mm)	Heat flux (W/mm^2)	Pipe bending (mm/m)
1	5	5.5	0.001
2	30	0.757	0.14
3 (optimal)	84	0.757	0.756
4	110	0.757	0.42

Fig. 8. Resistant zone in different heating radii.

Fig. 9. Residual equivalent plastic strain distribution in different cases, (a) case 1, (b) case 2, (c) case 3, (d) case 4.

the thickness) at the end of the heating time. As can be seen, in case 2, the tensile plastic strain in the resistant zone of the pipe section is almost zero. But in case 3, optimal case, the tensile plastic strain in the resistant zone and the compressive plastic strain in the heating zone are considerable. Further extension of the heating zone in case 4 leads an increase in the tensile plastic strain of the resistant zone. In this case, the large area of the heated zone causes a decrease in the average pressure of resistant zone and a significant reduction in the compressive plastic strain.

Figure 11 shows the distribution of the longitudinal plastic strain (ε_l) along a longitudinal path (average values through the thickness) in cases 2–4 at the end of the heating time. In case 3, optimal case, the compressive plastic strain is more substantial than other cases, resulting in further bending of the pipe after cooling.

The residual equivalent stresses (von Mises) in the optimal case are shown in Figure 12. The residual stresses are of paramount importance provided that the bent pipe working load is significant.

3.3 Simultaneous wide heating (SWH)

The tests conducted by Gatto et al. [4] revealed that the repetition of Spot Heating at a point with the same heating radius had no effect on the pipe bending angle. Furthermore, the bending angle will be reduced provided that the second heating has smaller radius. Also, the minimum distance for the repetition of heating in different points, across the pipe length, should be at least twice the heating zone diameter. This conclusion is founded on few tests and needs to be further explored.
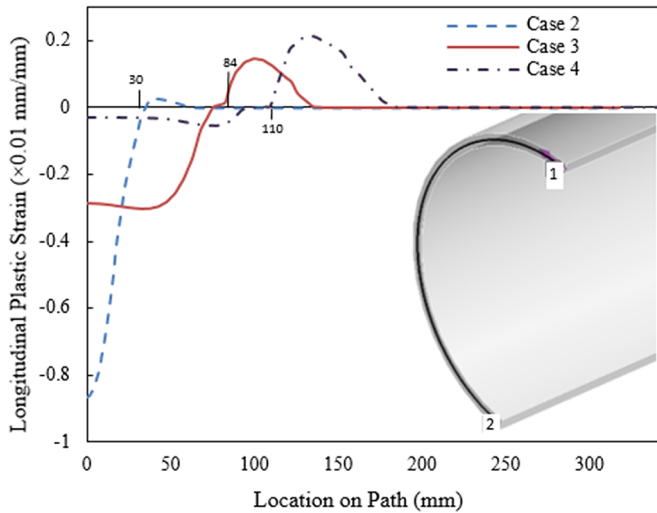
Fig. 10. Variation of longitudinal plastic strain (ε_l) along a circumferential path at the end of heating time.
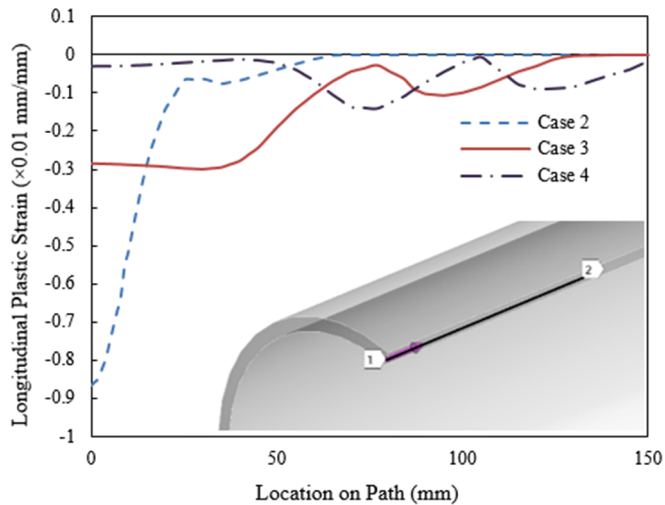

Fig. 11. Variation of longitudinal plastic strain along a longitudinal path at end of the heating time.

Some studies have been conducted on the repetition of the heating in the same zone in the Holt method for bending the thick pipes which led to an increase in bending angle [2,4].

Notably, various studies have defined re-heating as repetition of heating in a zone after the piece is cooled in first heating. However, in this section, heating two different zones are investigated simultaneously and non-simultaneously. In the Simultaneous Wide Heating (SWH, Fig. 2b), two regions are heated at the same time, while in the non-Simultaneous Wide Heating (non-SWH, Fig. 2c), the second zone is heated after heating and cooling the first zone.

Knowing the nature of deformation mechanism in wide heating (Sect. 3.2), it can be concluded that the interface zone is subjected to intense compression by heating two zones simultaneously. Therefore, compressive plastic strain and pipe bending angle will increase consequently.
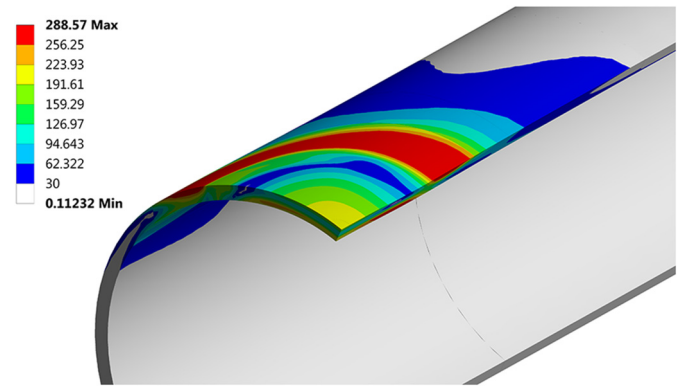
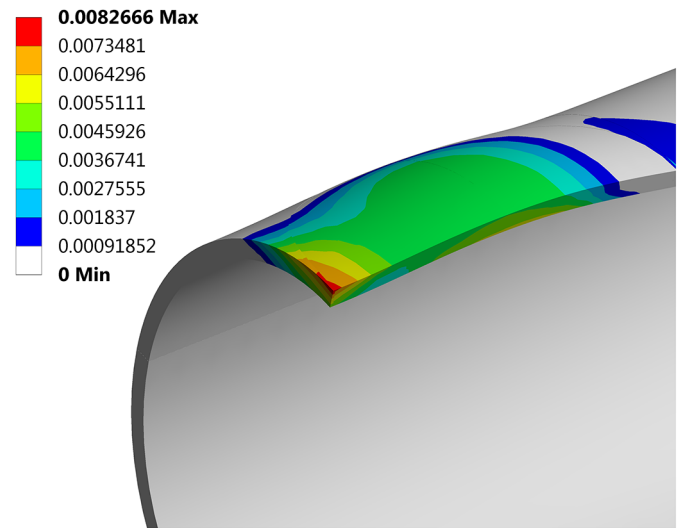

Fig. 12. Residual von Mises stress in case 3.

Fig. 13. Plastic strain in simultaneous wide heating (SWH) of two zones at the end of heating step.

Figure 13 shows the plastic strain at the end of the heating stage for two tangent zones, located along the pipe axis, in the SWH. As it can be observed, the interface zone is subjected to a significant plastic strain. The optimum pipe bending angle in this method increases to 2.196 mm/m, 2.9 times that observed in the wide heating of a single zone.

Figure 14 demonstrates the effect of the center-to-center distance between the two zones on the pipe bending angle in the SWH and non-SWH by a heating radius of 80 mm. A distance of 160 mm between tangent zones in SWH generates a pipe bending angle of 2.196 mm/m, 1.7 times that of the non-SWH method and 2.9 times that of the wide heating of single region (0.756 mm/m). By increasing the distance between the zones, the interaction effect is reduced, and the response of the two heating methods tends to a value twice the bending angle observed in the single zone heating (2*0.756). Moreover, with the coincidence of two zones at zero distance, the bending angle in non-SWH tends to 0.854 mm/m, which is slightly more than that observed in the single zone method. Therefore, the repetition of heating in a single zone is negligibly beneficial which is in good agreement with the results obtained by Gatto et al. [4] for the spot heating. Notably,
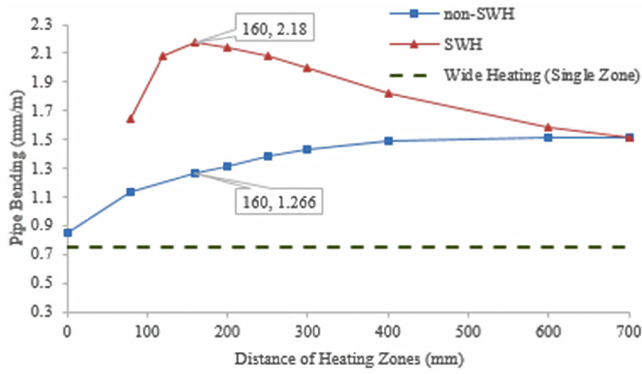
Fig. 14. Effect of distance between two zones on the pipe bending angle.

Table 3. Comparison of the pipe bending in different methods.

Method	Bending (mm/m)	Heating radius (mm)
Spot heating [4]	Few hundredths*	20
Holt	2.5	20 (effective radius)
Improved spot heating [8]	0.29	65 (effective radius)
Wide heating (single zone)	0.756	84
Simultaneous wide heating	2.196	80

* Depending on the heating conditions.

the simultaneous heating within two zones at distances of less than 160 mm leads to interference of the zones which is complicated in practice due to the interference of the torches.

Finally, heating two tangent zones in the SWH results in a pipe bending angle of 2.196 mm/m, 0.88 times that of the Holt method (2.5 mm/m). This value is obtained not needing to control the torch speed and path.

3.4 Comparison of different methods

Results obtained by different methods are compared in Table 3.

Figure 15 shows a schematic representation of the bending angle in the different heating methods.

4 Pipe heating test and torch calibration

To evaluate the results of numerical model, the heating test is performed on a seamless SA-106 pipe with an inner diameter of 203.2 and a thickness of 8.18 mm, identical to the simulation. The pipe is vertically fixed to the table by a four jaw chuck where two indicators are used with a precision of 0.01 mm to accurately record the displacements, as shown in Figure 16.
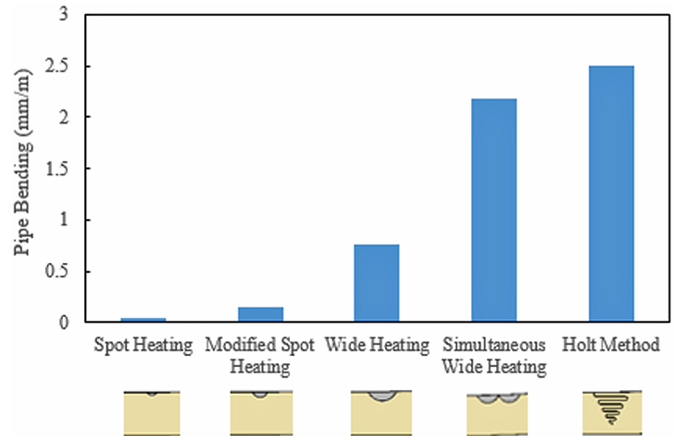

Fig. 15. Comparison of pipe bending angle in different heating methods.

Fig. 16. Pipe wide heating test. (a) Torch heads, (b) spot welder, (c) half pipe calibration test, (d) main test.

4.1 Torch calibration

Determining heat input is one of the most important problems with the torch. In this study, an infrared thermal camera (thermo-vision) was used to determine the surface temperature distribution. The laser-contact (k type) thermometer (Marmonix[TM]) is used to determine the emissivity coefficient and also to record the surface temperature changes at the heating zone centroid. The contact thermometer was connected to the heating zone center at the pipe inner face using an electric discharge spot welder. Since the flame prevents accurate measurement of the pipe surface temperature by infra-red radiation, the temperature behind the heating face, inner face of the pipe, was merely measured. To that end, a half-pipe is cut from the same pipe and the torch is installed in front of its outer face so that the inner face temperature is measured by the
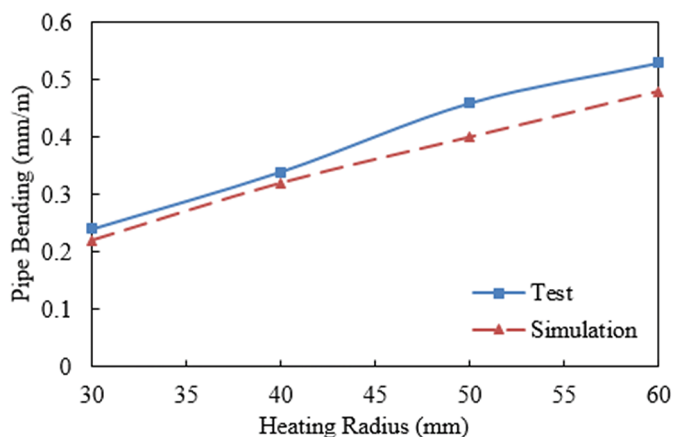
Fig. 17. Comparison of pipe bending angle between test and simulation.

laser probe (Fig. 16c). After recording the temperatures, the thermal flux in the same FE model is changed to bear the same temperature changes. Furthermore, the inlet gas flow and the torch distance can vary such that the temperature variations over time become similar to that of the FE model analysis.

4.2 Main test

The main test was carried out using the applied torch in the calibration test, without turning off the torch or any change in the gas intake, with the same distance from the surface to create an identical heat distribution. The heating zone radius varies from 30 to 60 mm and the flame intensity is set $0.76 \, \text{W/mm}^2$. It is worth noting that adjusting the heat intensity requires the torch flame calibration to be repeated. The final bending of the pipe is shown in Figure 17 where the results show an error ranging between 8% and 13%. Furthermore, it is revealed that increasing the heating radius increases the error.

5 Conclusion

To increase the bending angle in thick-walled steel pipes, wide heating with a uniform distribution was simulated along with a precise investigation of the deformation mechanism. Wide heating was proposed and optimized to extend the shortening mechanism and achieve the maximum bending of $0.756 \, \text{mm/m}$. Moreover, a new method using simultaneous wide heating (SWH) within two tangent zones was assessed. The pipe bending angle increased to $2.196 \, \text{mm/m}$ which is 0.88 times that observed in the Holt method $(2.5 \, \text{mm/m})$. Implementing this method, there would be no need for control over the torch velocity and path, as well as an easier control of the temperature.

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