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Simulation studies of the use of a new flexible mandrel design in the cold mechanical bending process of thin-walled pipes

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ABSTRACT

The paper presents the results of model tests related to the process of forming a pipeline arc using the mechanical bending method with a new flexible mandrel design. The introductory section outlines the problems associated with the pipeline manufacturing process and the methods and tools used to shape bent pipeline sections, in particular the so-called mandrel bending. The shortcomings of the currently used cold pipe bending methods and the need to search for new solutions in this area are pointed out. The main part of the paper consists of the results of model tests of deformations and stresses resulting from the process of forming a mechanically bent pipeline arc using the proposed version of the mandrel, which has the properties of flexible adaptation to the shape of the formed pipe while maintaining radial stiffness. The model studies included an analysis of the values of deformations and stresses occurring in the cross-section of a bent pipe arc depending on changes in the design parameters of the flexible mandrel using the finite element method. Based on the obtained test results, the design parameters of the flexible mandrel were determined, thanks to which the stresses in the cross-sections of the bent pipe section caused using the mandrel are within the limits imposed by normative recommendations, while eliminating the ovalisation of the cross-section of the shaped pipe. This demonstrates the practical usefulness of the proposed flexible mandrel with a new design. The innovative nature of the proposed solution is determined by the fact that the mandrel is characterised by flexible susceptibility to bending deformation, while maintaining radial rigidity. The presented flexible mandrel also allows pipes to be shaped using traditional methods without the need for specialised and expensive mandrel bending machines.

Keywords: pipelines, flexible mandrel bending, stress and strain modelling, cross-sectional geometry assessment, finite element simulations.

INTRODUCTION

In many sectors of the economy, the distribution of working energy sources (liquids, gases) is carried out using transmission fittings. Conventional power plants [1], gas pipelines [2] and waste incineration plants [3] are examples of such sectors. Transmission fittings are also an important and essential component of a number of industries, such as the automotive, aviation, aerospace, and the broadly understood maritime industry and related entities, including the shipbuilding industry [4–6]. The pipeline route is planned in accordance with the guidelines of a technologist [7]. Nevertheless, it is frequently adjusted to secondary structures (ceilings, beams, foundations). Therefore, it includes both straight and bent sections [8]. Transmission fittings are consequently installed by means of straight and bent pipe sections and different types of connectors, couplings, reducers and flanges. Accompanying and measuring equipment, such as valves, gate valves, orifices, dampers, expansion devices and pressure gauges, are also mounted on the pipeline route.

In terms of the effects of the production process for different types of pipeline components, the fabrication of bent pipeline sections is especially noteworthy.

In the bending process, ovalisation of the cross-section occurs with a concomitant variation in the wall thickness of the pipe around its circumference [9,10]. The bending process is often associated with an increased level of residual stresses in the bent pipe, necessitating appropriate heat treatment (i.e. stress relief) after completion of the product manufacturing process. Cross-sectional changes disrupt the flow of the working medium and hinder cleaning and maintenance, which are required to keep the pipeline operational. These changes further reduce the strength of the bent element in the tension region due to the thinning of the pipe wall [11]. Furthermore, as ovalisation increases, the accuracy of stress distribution calculations along the pipeline route decreases [12]. An ideally circular cross-section has a different distribution of pressure than an elliptical cross-section. Therefore, pipe sections formed by bending are assessed for their dimensional and shape compliance in accordance with prevailing standards (for comparison, see [13]). The standards from the EN 13480 group [14–17] are an example of a standard applicable to the energy industry in this regard. It specifies the allowable waviness of the compressed layer, the maximum allowable ovalisation and the minimum wall thickness in the tensioned layer.

Several primary bending methods tailored to specific types of pipes are used in industrial conditions, depending on the type of technology employed. Generally, it is possible to distinguish between two types of pipe bending technologies: cold [18–20] and hot [21–23].

The so-called mandrel bending is one of the most modern and advanced technologies of mechanical cold bending of pipes [24]. This method is particularly suitable for forming pipes with a very small bending radius [25] and involves inserting a so-called mandrel into the centre of the pipe being shaped during the process. According to the type of bent pipe and the bending radius, the pipe is filled with straight, ball or segment mandrels (especially in the case of bending tubes) [11,26]. The use of a mandrel in the pipe (or tube) bending process prevents deformation, creasing of the bent arc, or its flattening and collapse. It is possible to achieve greater control over the desired ovalisation of pipes. The use of mandrel bending technology also helps to counteract the tendency of the material to return to its original shape during the process.

As emphasised earlier, mandrel bending is a technique mostly applied to pipes with small bending radii (where they have a dimension representing three times the external diameter of the pipe) [27]. The mandrel adjusts the plastic flow of the material in the processing area to ensure the specified bending radius of thin-walled pipes and prevent unwanted deformation of the bent section of the pipeline [28]. A mandrel must be used if the diameter of the pipe is at least twenty times greater than its thickness [27]. If not, bending pipes with a mandrel isn't essential because the forces in the processing area aren't strong enough to induce corrugation in the pipe.

The key to the effective use of a mandrel is the correct positioning of its face relative to the bending point. This ensures that the shape of the mandrel face is correctly reproduced on the vertical cross-section of the pipe. The factor limiting the projection of the mandrel is the point of intersection of its outer contour with the inner wall of the pipe. It is generally recommended that the face of the mandrel (excluding its radius) be positioned at a distance of approximately 2/3 of the distance between the point of intersection and the bending axis. However, this causes a slight flattening of the cross-section of the pipe on the outer part of the bending radius. This phenomenon is inevitable due to the bending stresses generated. Pushing the mandrel too far forward may cause bulging and cracking of the pipe wall. On the other hand, pulling it back too far may cause significant flattening of the pipe cross-section, increased friction and even damage to the mandrel.

Mandrel bending machines are used for mandrel bending of pipes [29,30]. These machines are designed for bending pipes using the rotary method, i.e. winding the pipe onto a die. The pipe is cold-formed in such a way that the outer wall of the bent arc is tensioned, and the inner wall is compressed. From the outside, the pipe is pressed against the die by means of a pressure plate that rotates together with the die and is supported by a pressure bar. In some cases, it is also necessary to support the pipe on the opposite side of the bar with a smoother to prevent folds from appearing on the inside of the bend. From the inside, the pipe is filled with a mandrel, which prevents the walls from collapsing inwards and flattening. An additional way to reduce the occurrence of undesirable bending effects is to use special tooling [31].

Recently, research on pipe bending using flexible mandrels has been increasingly undertaken. Below is a brief overview of selected research results in this field. Liu et al. [32] conducted numerical and experimental studies on the rotary bending of rectangular H96 brass tubes with double ridges, using rigid mandrels and polyvinyl chloride (PVC) mandrels. The results showed that the PVC mandrel has a better damping effect on the deformation of the longer side of the cross-section, the deformation of the shorter side of the cross-section, and the deformation of the gap between the bottom of the tube's ridge grooves. The bending properties of bimetallic composite tubes using a rigid mandrel and five flexible mandrels made of polytetrafluoroethylene (PTFE), polyethylene (PE), polypropylene (PP), polyformaldehyde (POM) and PVC were compared in [33]. PTFE, PE and PP mandrels have shown similar performances, which are less effective in reducing cross-sectional collapse rates. However, they are better at minimising damage caused by bending and wall thinning. Rigid, POM and PVC mandrels have shown similar performances and are more effective at preventing cross-sectional collapse. Mandrels with higher hardness, such as rigid, PVC and POM mandrels, are better at preventing cross-sectional collapse but are more likely to cause tube crack. In turn, the process of bending thin-walled pipes using a polyurethane mandrel is presented in [34,35].

The above-mentioned publications described the use of flexible mandrels, whose deformability results from their material properties. The second group of flexible mandrels are those whose deformability results from their structural design. Wang et al. [36] designed a special mandrel with an adjustable diameter for bending thin-walled pipes, constructed from ball core segments, with an adjustment mechanism based on a planetary gear. Various applications of mandrels with single-core or multi-core ball connectors, but with a simpler design, are presented in [37–41]. In contrast, the use of a mandrel with multi-core cylindrical connectors suitable for bending rectangular tubes is reported by Zhu et al. [42,43]. Investigation of floating ball mandrel application in tube free bending is described in [44]. Li et al. [45] proposed a diameter-adjustable multi-point contact mandrel consisting of several segments with support blocks that move radially. Another type of mandrel proposed for use in rotary pipe

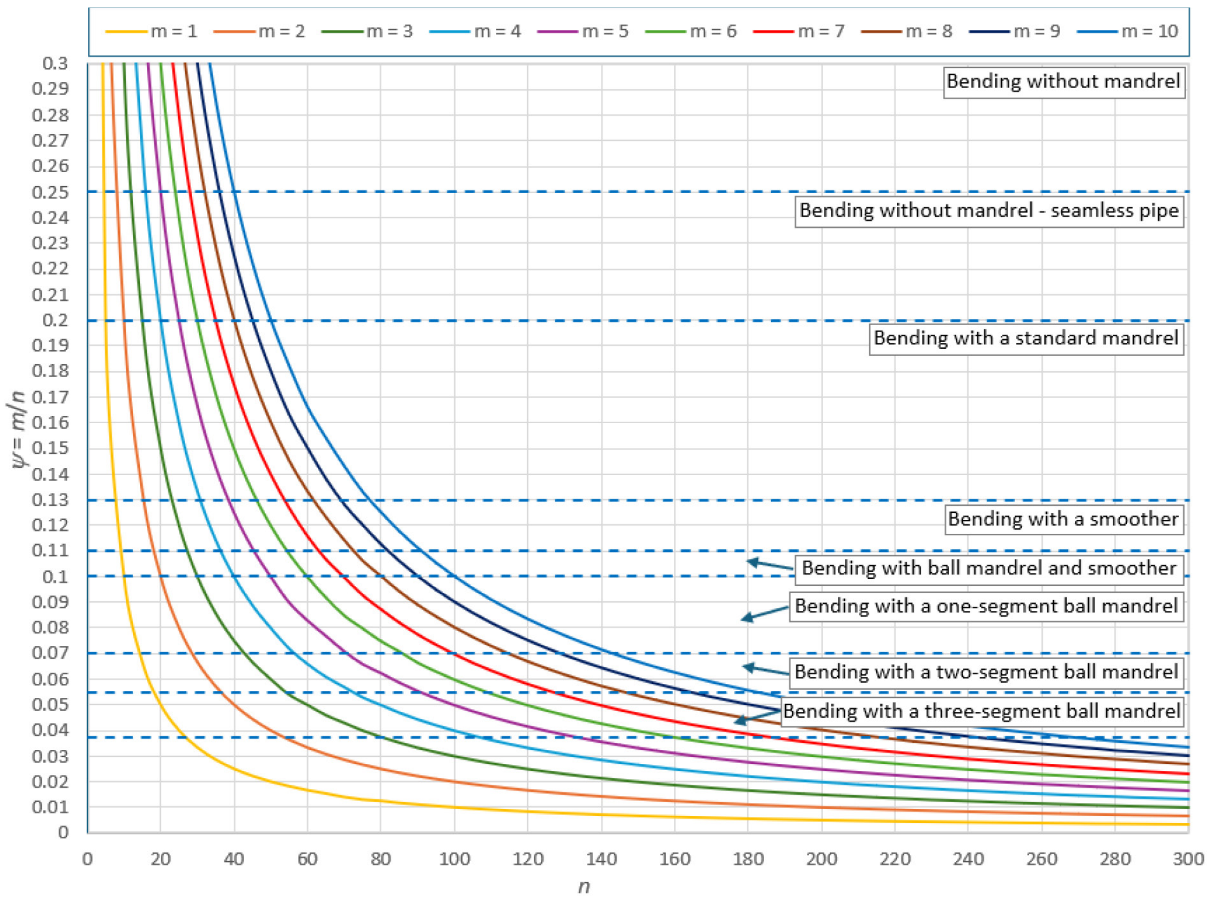


Figure 1. Comparison of cold pipe bending methods and their limitations

bending is a mandrel in which the segments are connected by chain links [46,47]. Besides the aforementioned solutions for mandrels used for bending pipes, there are also special design solutions for mandrels described in patent Pat.203569 [48] and in utility model Ru.058109 [49].

A comparison of cold pipe bending methods and their limitations is presented separately in Figure 1. It shows the applicability ranges of bending methods used in practice in relation to pipe geometric parameters, assuming the following dimensionless coefficients:

- m – representing the ratio of the bending radius R to the outer diameter D_o of the pipe,
- n – representing the ratio of the outer diameter D_o to the of the wall thickness g,
- Ψ – representing the ratio of m and n.

The mandrels presented above, with deformability resulting from their structure (including segments connected in various ways), have a rather complex structure. The use of these mandrels also requires the use of fairly complex equipment and, quite often, additional operations to improve the bending of pipes. Proposals for new patented solutions, on the other hand, are very modest. They have a complex design and are dedicated to specific products. These observations underlie the need to develop a new design solution for a flexible mandrel characterised by: versatility, simple design, applicability in various variants of the bending process, possibility of freely shaping the pipe in terms of radius, angle or mutual arrangement of bending planes, without the need to disassemble the mandrel, and ensuring that the manufactured products achieve the required dimensional and shape accuracy at low cost.

The purpose of this paper is to propose a new type of flexible mandrel for use in cold bending thin-walled pipes with a simple design and to describe the results of its preliminary model tests. The essence of this mandrel design is the use of a spring in its construction, and this design is the subject of patent application P.448923 [50]. A review of the literature shows that springs have not yet been used in mandrel designs for cold bending of pipes. The possibility of using springs in mandrel designs has only been discussed in relation to hot bending of pipes [51].

3D CAD modelling was used to model the mandrel [52,53], while the finite element method (FEM) was used for calculations [54–56]. The results of tests related to pipe ovalisation after bending were referred to the recommendations contained in the EN 13480-3 standard [16].

The structure of the paper is as follows. First, the essence of the new flexible mandrel is described. Next, the results of tests on deformations and stresses occurring in a sample bent pipe are described. Then, the test results are evaluated and the final conclusions from the tests are presented.

PURPOSE, INTENDED TECHNICAL EFFECT AND ESSENCE OF THE NEW FLEXIBLE MANDREL DESIGN

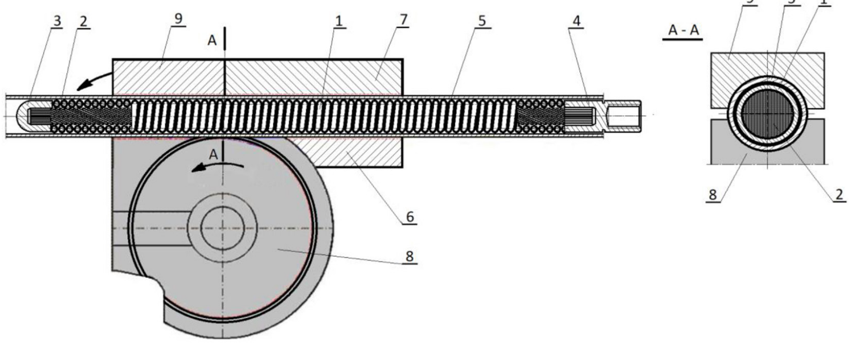
Taking into account the observations made during the literature review, it was proposed to use a new mandrel design in the pipe forming process, characterised by flexible susceptibility to bending deformation while maintaining radial stiffness. At the same time, a method of shaping pipes using the proposed flexible mandrel was also developed, which can be carried out using traditional methods without the need for specialised and expensive mandrel bending machines.

In order to achieve the desired technical effect, a flexible mandrel and a method of bending pipes using this flexible mandrel were designed, as shown in Figure 2.

They have the following characteristics [50]:

1. The flexible mandrel has the compact armour 1 made of wire on the outside in the form of a spiral spring. Spring steel 60S2 [57], which is resistant to high elastic deformation, can be used as the spring material. This steel is hardened in oil.
2. The mandrel armour is susceptible to bending deformation due to the fact that, at the final stage of production, it undergoes heat treatment to give it the required strength properties.
3. The mandrel armour has an external diameter corresponding to the internal diameter of the shaped pipe and is filled from the inside with the cord or the braid of flexible cords 2 clamped on one side by the spherical end 3 and on the other side by the clamping sleeve 4 ending with a threaded grip part in which the extractor is mounted to enable removal of the mandrel after the pipe bending process is complete.
4. The wire or wire braid completely fills the inner surface of the armour, maintaining the flexible bending properties of the mandrel on one side and its radial rigidity on the other.
5. After inserting the mandrel into the hole in the

a)



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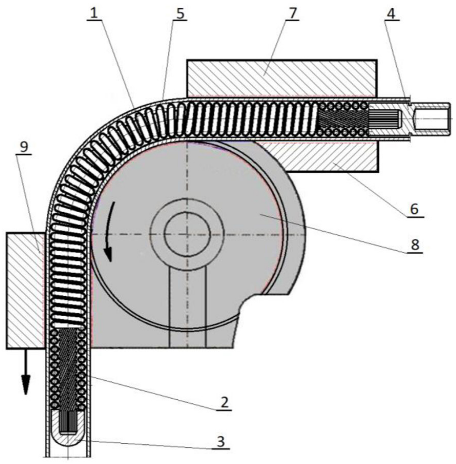

Figure 2. Proposal for a new flexible mandrel: (a) design, (b) method of use in the pipe bending process

pipe 5 and then fixing the pipe between the slide 6 and the clamp 7, the pipe with the flexible mandrel inside is bent and shaped by the rotating forming roller 8 and the pressure segment 9 coupled to it in real time.

When the forming process is complete and the clamp 7 and the pressure segment 9 are released, the mandrel is removed from the pipe hole using the mandrel extractor. The elastic stresses generated during pipe forming disappear, contributing to an increase in its cross-sectional dimensions, thus facilitating the removal of the mandrel from the hole.

The bending process is further described using the block diagram shown in Figure 3.

An alternative version of pipe bending is the bending technology shown in Figure 4. As before, the mandrel is placed into the hole in the pipe 5, and then the pipe is placed between the slide 6 and the clamp 7. The pipe, together with the flexible mandrel placed inside it, is then bent and shaped by the rotating forming roller 8 and the modified pressure segment 9 coupled with it, equipped with the rotating roller 10. After completing the forming process and releasing the clamp 7 and the pressure segment 9 equipped with the rotating roller 10, the mandrel is removed from the pipe hole using the extractor, which forms a screw connection with the threaded grip part of the clamping sleeve 4. As in the case of the bending technology discussed earlier, the stresses and elastic deformations generated during the shaping of the bent pipe arc disappear, contributing to an increase in its cross-sectional dimensions and facilitating the removal of the flexible mandrel from the hole.

From a practical point of view, the use of the proposed mandrel ensures that the circular cross-section of the pipe hole is maintained, and there are no restrictions on the shape of the pipe in terms of radius, angle or mutual arrangement of the bending planes. This solution can complement existing and commonly used pipe bending methods, guaranteeing the required dimensional and shape accuracy of manufactured products at a low cost.

The proposed mandrel can be used for bending thin-walled pipes with an external diameter of up to 50 mm.

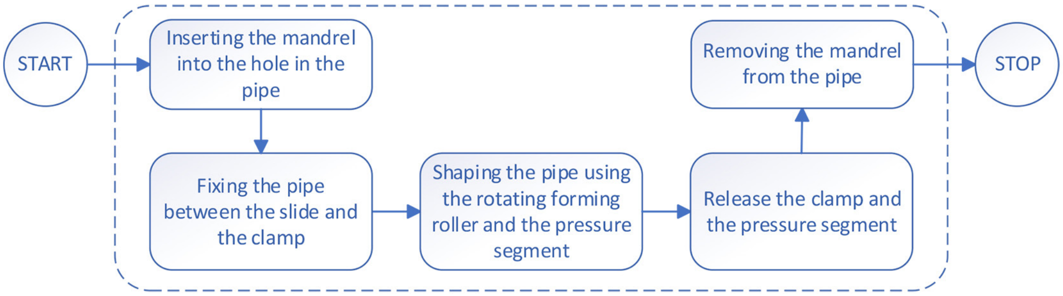

Figure 3. Block diagram of the bending process

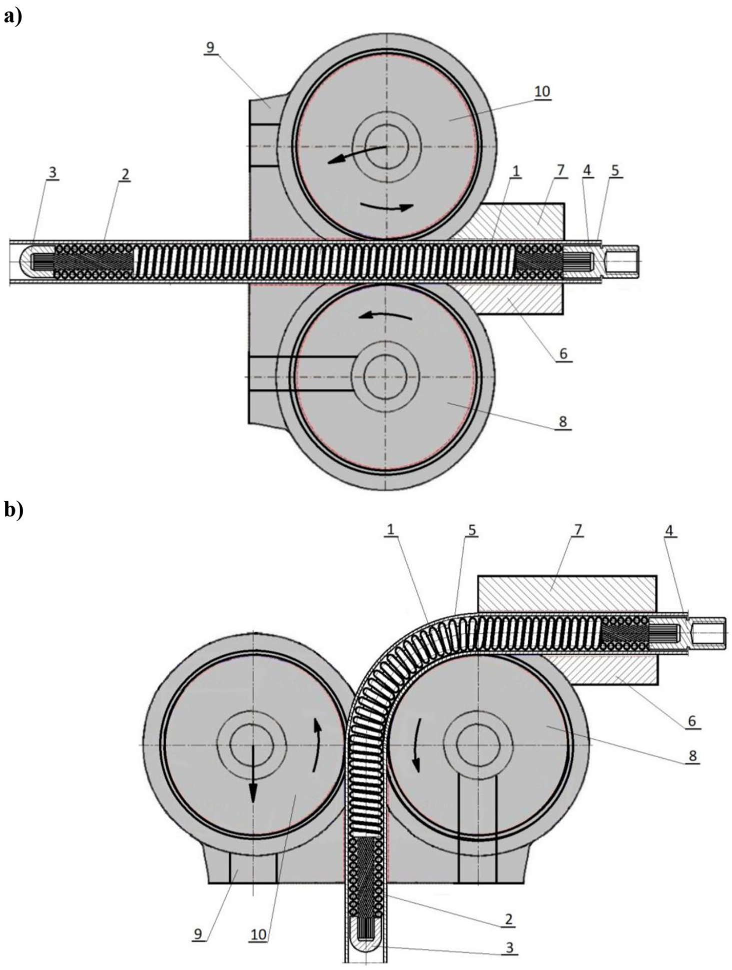

Figure 4. Proposal for a new flexible mandrel: (a) design, (b) method of use in the pipe bending process

The bending method using the proposed mandrel was tested under laboratory conditions using the device shown in Figure 5.

During laboratory tests, the following pipe parameters were assumed: D_o was 10 mm, g was 0.8 mm, the inner diameter D_i was 8.4 mm, and R was 23 mm.

The pipe with the mandrel fixed in the device at the beginning of the bending process is illustrated in Figure 6, while the pipe with the mandrel after completion of this process is illustrated in Figure 7. To assess the cross-sectional dimensions of a shaped pipe, a parameter called ovalisation was used, in accordance with the applicable standards [14–17] (taking the outer diameter of the pipe as the evaluation criterion), is determined by the following formula:

$$\Delta ov = \frac{2(D_{o\,max} - D_{o\,min})}{D_{o\,max} + D_{o\,min}} \cdot 100\% \quad (1)$$

where: $D_{o\,max}$ – maximum outer diameter, $D_{o\,min}$ – minimum outer diameter.

Figure 5. Device for testing the correctness of the bending process using the proposed mandrel

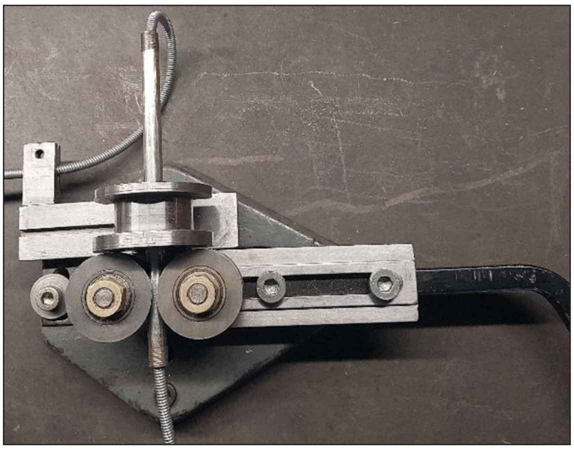

Figure 6. Beginning of the pipe bending process using the proposed mandrel

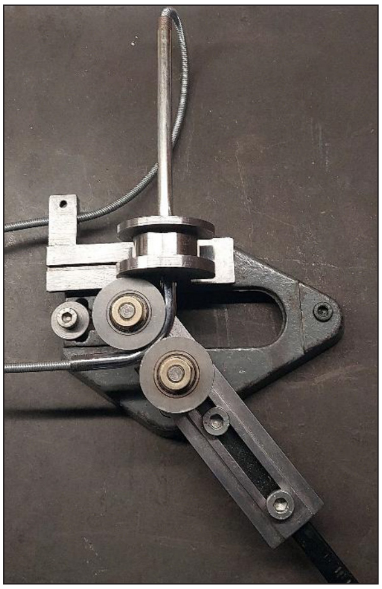

Figure 7. Completion of the pipe bending process using the proposed mandrel

By measuring the outer diameter of the pipe after the bending process using a calliper with an electronic readout accurate to 0.01 mm, the following values were obtained: $D_{o\,max}$ = 10.05 mm, $D_{o\,min}$ = 9.96 mm. For these values, the ovalisation value calculated on the basis of Equation 1 was 0.899%. At the same time, it is less than 1% of the permissible ovalisation value determined on the basis of EN 13480-3 [16], which is 8.869%.

The results of the laboratory tests described above indicate very good pipe bending properties and justify further research. The results of the numerical tests are presented later in this paper, while a more comprehensive experimental study of the bending process using the proposed mandrel will be conducted in the future.

DEFORMATION AND STRESS TESTING IN A BENT PIPE SECTION USING THE PROPOSED FLEXIBLE MANDREL

The application properties of the proposed flexible mandrel design were verified by simulation tests of deformations and stresses in a thin-walled pipe section bent at an angle of 90°. The simulations were carried out using the Midas NFX numerical strength calculation programme [58,59], applying the module for non-linear analyses.

Deformation and stress simulations were carried out for a bent pipe without and with the flexible mandrel [60], changing the spacing between the forming segments. The calculations were performed for three models with the following designations:

- MW – model without a mandrel
- M1 – model with a mandrel with segments spaced at 2 mm intervals,
- M2 – model with a mandrel with segments spaced at 1 mm intervals.

The M1 and M2 models differ only in the spacing between the individual segments in the mandrel model. The other parameters of both models are identical.

The following parameters were set for the pipe: D_o equal to 32 mm, g equal to 2.1 mm, D_i equal to 27.8 mm. The bending radius R was 84 mm. These conditions guarantee that the properties of the tested pipe correspond to those of thin-walled pipes, for which the following relationship applies [12]:

$$\frac{g \cdot R}{D_o^2} < 0.2 \quad (2)$$

The material selected for the pipe was P265GH boiler steel [61], with variable strength characteristics shown in Figure 8.

The shaping system together with a section of pipe modelled in FEM for model M1 is shown in Figure 9. The light blue colour indicates a section of the pipe, the dark blue colour indicates 19 forming segments modelling the mandrel, and the yellow colour indicates the rotating forming roller. Hexagonal elements were used to construct the model. The characteristics of the finite element mesh of the model are summarised in Table 1.

In addition to the finite elements listed in Table 1, rigid elements were used in the model to simulate the non-deformability of the roller (forming segment) and mandrel (for models M1 and M2). The view of rigid elements used in modelling the mandrel segments is shown in Figure 10 (for comparison, see [62,63]).

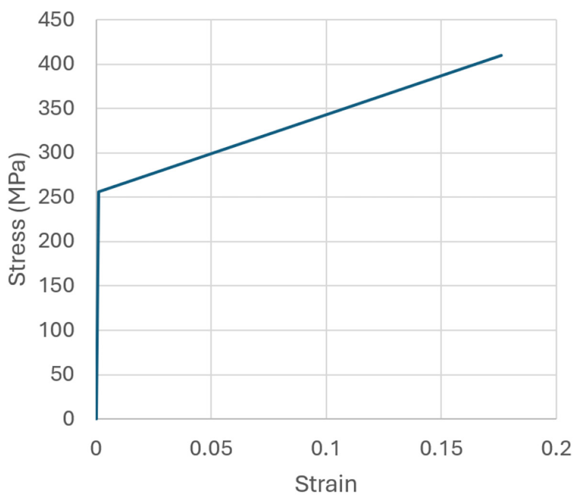

Figure 8. Elastic-plastic characteristics of P265GH boiler steel used as the pipe material

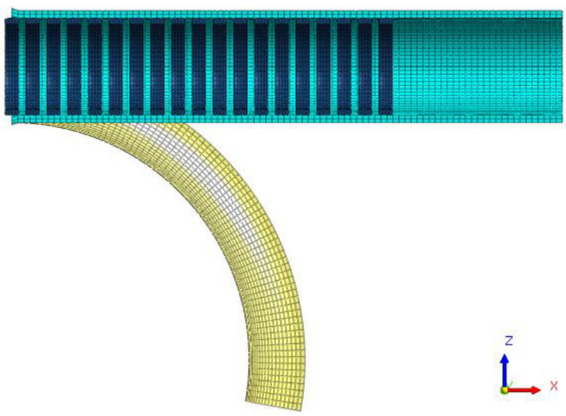

Figure 9. FE-model of the shaping system with a section of pipe

The characteristics of the contact elements in the pipe forming system model are shown in Table 2. The view of contact elements used in modelling (in the case of model M1) is shown in Figure 11 (for comparison, see [64]). Master elements are shown in brown, while slave elements are shown in purple.

General contact elements [65,66] were used between the pairs pipe-left roller, pipe-right roller and pipe-mandrel. The following contact element parameters were adopted:

- scaling factor of normal stiffness equal to 1,
- scaling factor of tangential stiffness equal to 0.1,
- coefficient of friction equal to 0.01.

The accepted friction coefficient value applies to the friction interaction between the pipe and other elements in individual bending models and is consistent with the practice used in FEM-based modelling [67,68]. All boundary conditions in individual models are fixed.

The results of simulation tests of deformations in a pipe section bent without the use of the proposed mandrel (i.e. for model MW) are shown in Figure 12.

The results of simulation tests of stresses in a pipe section for model MW are shown in Figure 13. In particular, Figure 13a shows the results of tests of maximum reduced stresses σ_{red} according to the Huber – von Mises – Hencky yield criterion [69] in the cross-section located at 45° for a bent pipe. Figure 13b, on the other hand, shows the results of analogous tests for maximum equivalent stresses σ_{eq} determined at integration points for non-linear analysis and elasto-plastic material [70].

The results of simulation tests of deformations in a pipe section for model M1, before removing the mandrel, are shown in Figure 14. Analogous deformation maps after removing the mandrel are shown in Figure 15.

The results of simulation tests of maximum reduced stresses σ_{red} according to the Huber – von Mises – Hencky yield criterion [69] in a pipe section for model M1 are shown in Figure 16. In particular, Figure 16a shows the results of tests before removing the mandrel. Figure 16b, on the other hand, shows the results of analogous tests after removing the mandrel. Figure 17 shows the results of analogous tests for maximum equivalent stresses

Table 1. Characteristics of the finite element mesh of the pipe forming system model

Model part	Number of finite elements	Number of nodes
Pipe	7.280	11.316
Flexible mandrel	4.256	5.510
Roller (forming segment)	1.500	3.192

Figure 10. View of rigid elements used in modelling mandrel segments

σ_{eq} determined at integration points for non-linear analysis and elasto-plastic material [70].

The results of simulation tests of deformations in a pipe section for model M2, before removing the mandrel, are shown in Figure 18. Analogous deformation maps after removing the mandrel are shown in Figure 19. The results of simulation tests of maximum reduced stresses σ_{red} according to the Huber – von Mises – Hencky yield criterion [69] in a pipe section for model M2 are shown in Figure 20. In particular, Figure 20a shows the results of tests before removing the mandrel. Figure 20b, on the other hand, shows the results of analogous tests after removing the mandrel. Figure 21 shows the results of analogous tests for maximum equivalent stresses σ_{eq} determined at integration points for non-linear analysis and elasto-plastic material [70].

A summary of the results of simulation tests of changes in the dimensions of the shaped pipe resulting from deformations caused by bending is presented in Table 3.

A summary of the results of simulation tests of reduced stresses σ_{red} changes in the shaped pipe section resulting from deformations caused

Table 2. Characteristics of contact elements in the pipe forming system model

Contact location	Number of master elements	Number of slave elements
Pipe – Roller	1.500	1.820
Pipe – Flexible mandrel	2.128	3.640

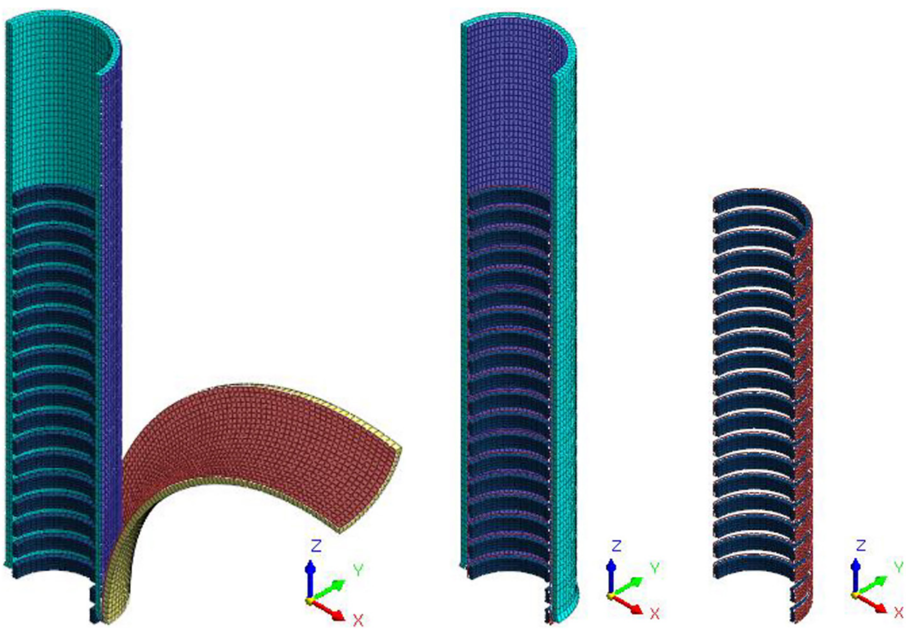

Figure 11. View of contact elements used in modelling (for model M1)

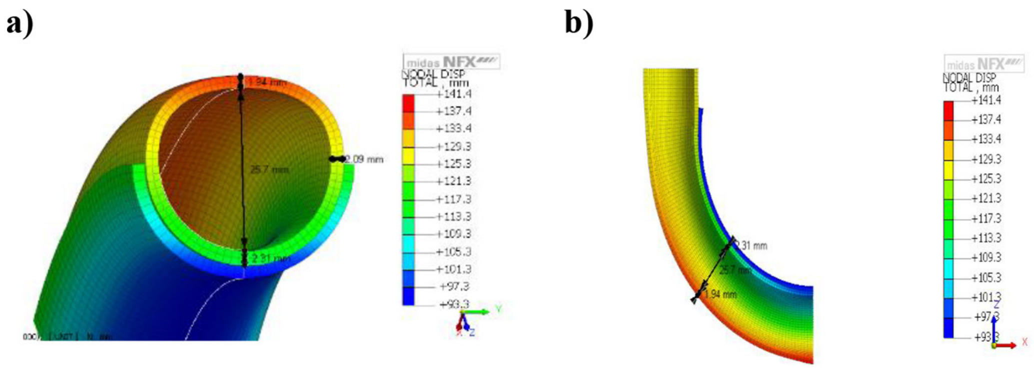

Figure 12. Results of pipe deformation simulation tests for model MW: a) in transverse cross-section (at an angle of 45°), b) in longitudinal cross-section

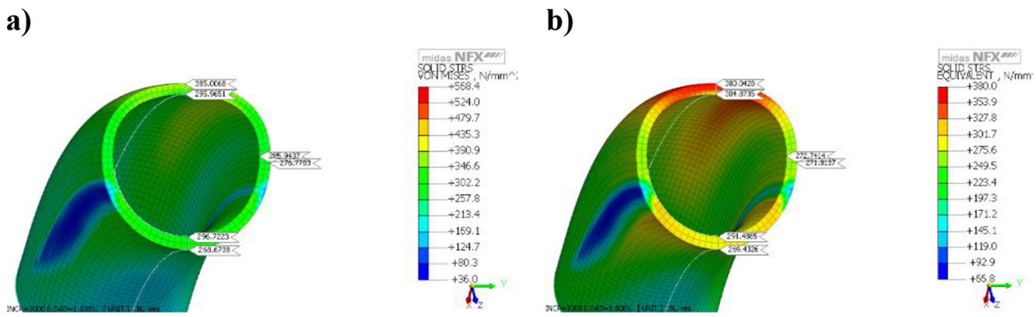

Figure 13. Results of stress simulation tests for model MW in transverse cross-section (at an angle of 45°): a) reduced stresses σ_{red}, b) equivalent stresses σ_{eq}

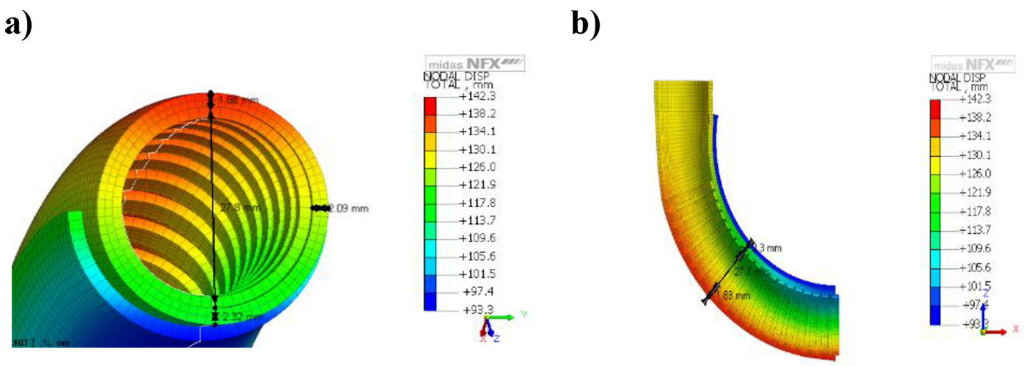

Figure 14. Results of pipe deformation simulation tests for model M1, before removing the mandrel: a) in transverse cross-section, b) in longitudinal cross-section

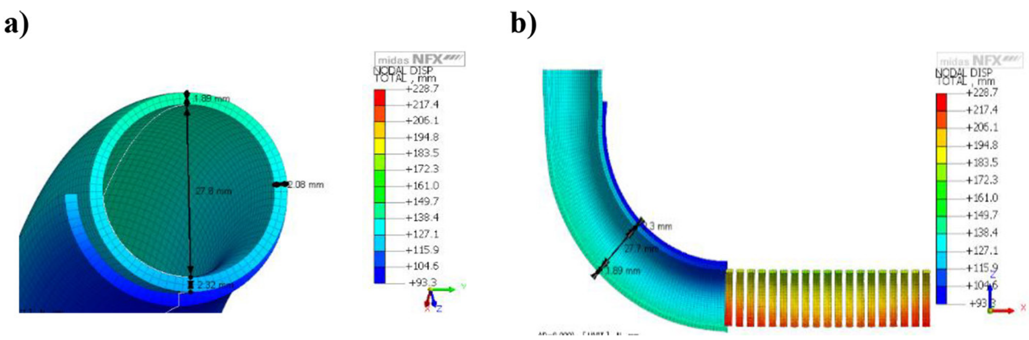

Figure 15. Results of pipe deformation simulation tests for model M1, after removing the mandrel: a) in transverse cross-section, b) in longitudinal cross-section

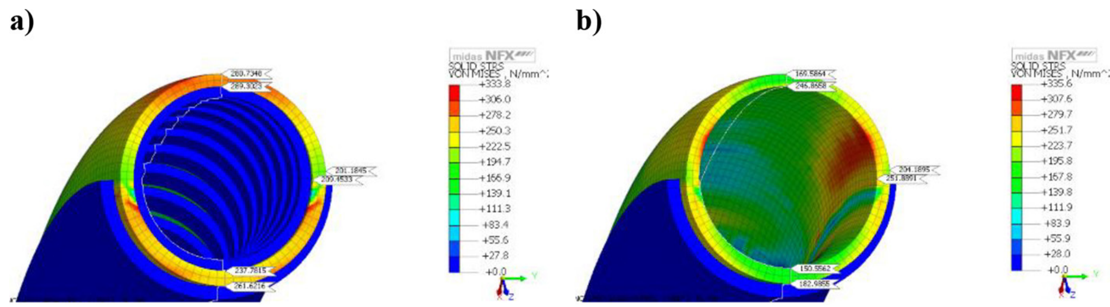

Figure 16. Results of reduced stresses σ_{red} simulation tests for model M1: a) before removing the mandrel, b) after removing the mandrel

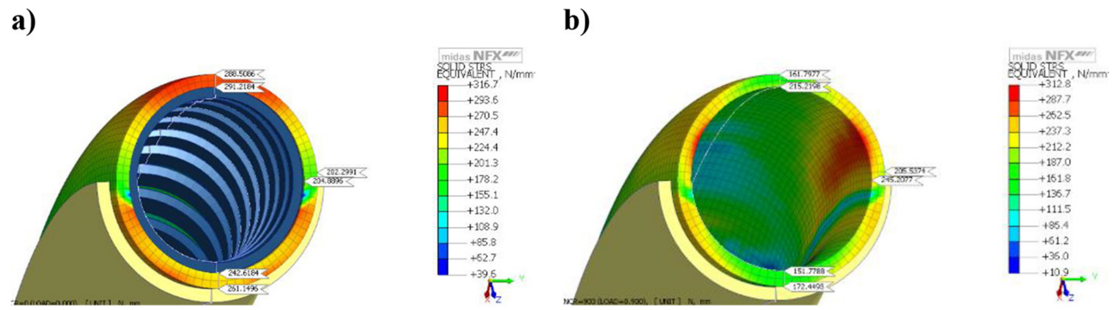

Figure 17. Results of equivalent stresses σ_{eq} simulation tests for model M1: a) before removing the mandrel, b) after removing the mandrel

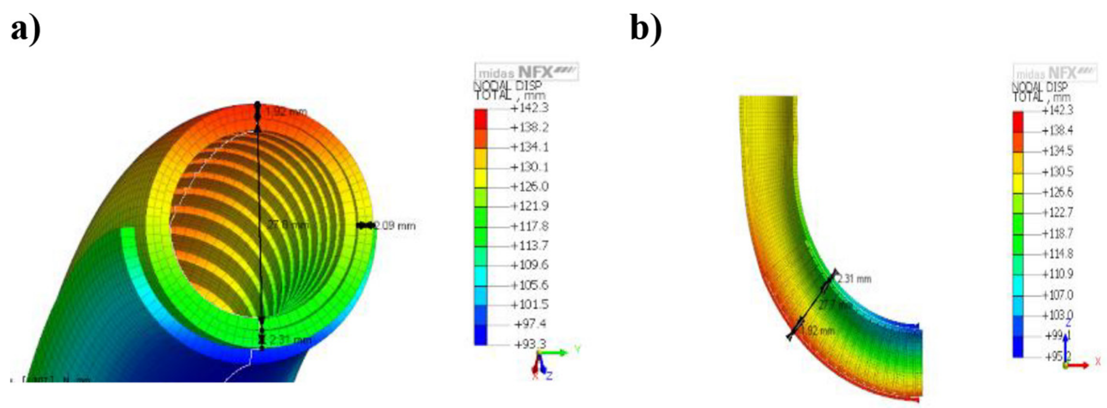

Figure 18. Results of pipe deformation simulation tests for model M2, before removing the mandrel: a) in transverse cross-section, b) in longitudinal cross-section

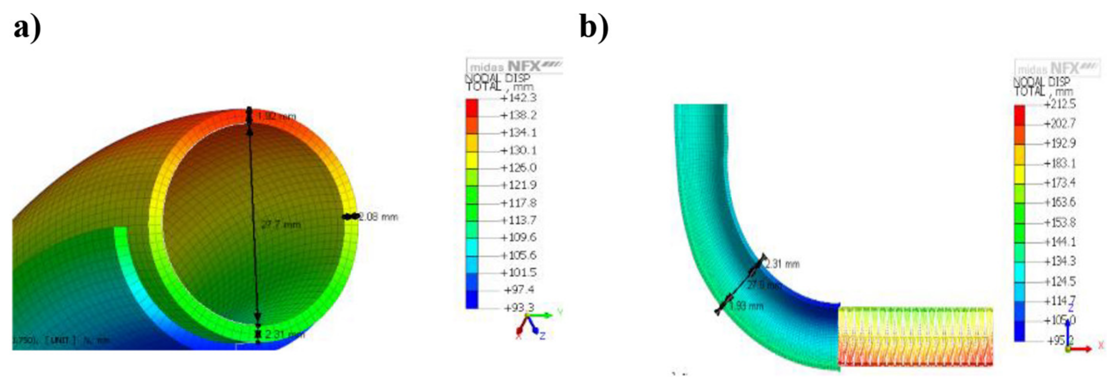

Figure 19. Results of pipe deformation simulation tests for model M2, after removing the mandrel: a) in transverse cross-section, b) in longitudinal cross-section

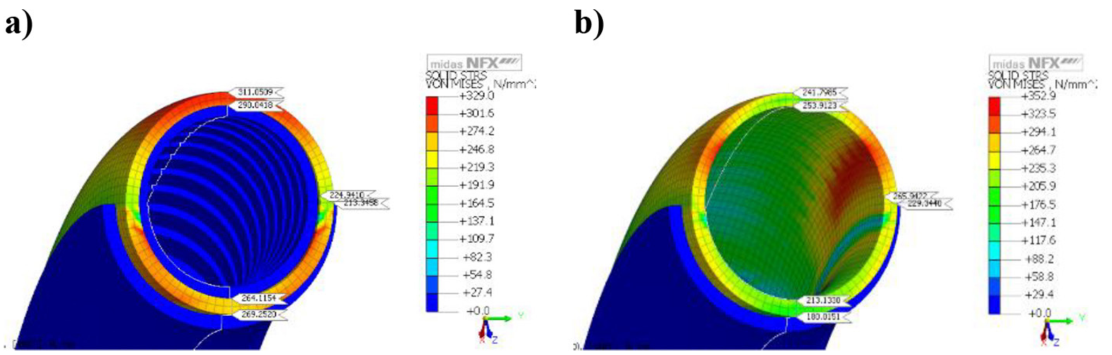

Figure 20. Results of reduced stresses σ_{red} simulation tests for model M2: a) before removing the mandrel, b) after removing the mandrel

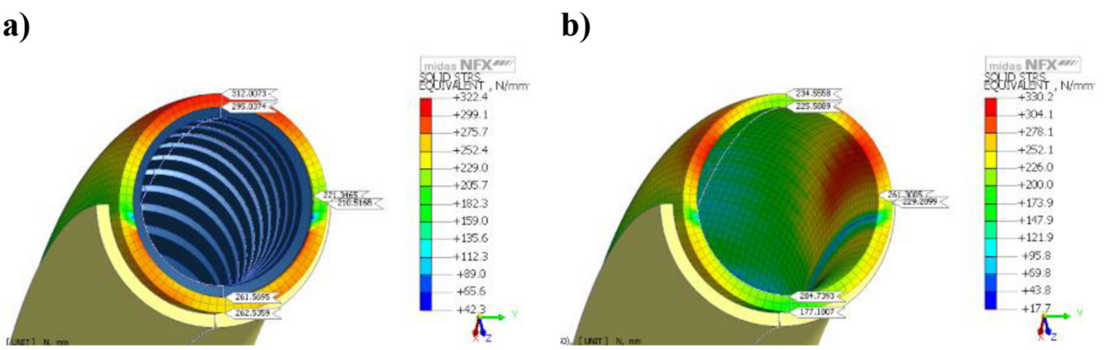

Figure 21. Results of equivalent stresses σ_{eq} simulation tests for model M2: a) before removing the mandrel, b) after removing the mandrel

Table 3. Summary of simulation results for changes in the dimensions of the shaped pipe resulting from deformations caused by bending

Model symbol	Pipe wall thickness in the vertical direction on the compressed side t_{vc}	Pipe wall thickness in the vertical direction on the tensioned side t_{vt}	Internal diameter of the pipe in the vertical direction	Outer diameter of the pipe in the vertical direction	Pipe wall thickness in the horizontal direction t_h	Internal diameter of the pipe in the horizontal direction	Outer diameter of the pipe in the horizontal direction
	mm						
MW	2.31	1.94	25.70	29.95	2.08	27.84	32.00
M1	2.31	1.93	27.70	31.94	2.10	27.80	32.00
M2	2.29	1.93	27.80	32.00	2.09	27.82	32.00

by bending is presented in Table 4. An analogous summary for equivalent stresses σ_{eq} is provided in Table 5. The values obtained from numerical simulations (given in full in Tables 3 to 5) are also summarised graphically in Figures 22 to 24.

RESULTS

An essential parameter used in evaluating the cross-sectional dimensions of shaped pipes is ovalisation Δov, which can be calculated from Equation 1 given earlier in the paper. The permissible ovalisation value relative to the bending radius R and the outer diameter D_o of the bent pipe is determined from the following dependence:

$$\Delta\, ov_p = \frac{20}{\frac{R}{D_o}} = \frac{20}{m} \quad (3)$$

Figure 25 presents a graph illustrating the change in permissible ovalisation Δov_p as a function of the m coefficient. It was prepared on the basis of EN 13480-3 [16], according to which the maximum ovalisation value in the

Table 4. Summary of the results of simulation tests of reduced stress σ_{red} changes in the shaped pipe section resulting from deformations caused by bending

Model symbol	Reduced stresses in the pipe on the outer side of the wall compressed in the vertical direction $\sigma_{red\ ovc}$	Reduced stresses in the pipe on the inner side of the wall compressed in the vertical direction	Reduced stresses in the pipe on the inner side of the wall tensioned in the vertical direction	Reduced stresses in the pipe on the outer side of the wall tensioned in the vertical direction $\sigma_{red\ ovt}$	Reduced stresses in the pipe on the outer side of the wall in the horizontal direction $\sigma_{red\ oh}$	Reduced stresses in the pipe on the inner side of the wall in the horizontal direction
	MPa					
MW	302	291	296	385	288	293
M1	181	167	252	239	198	281
M2	184	202	213	269	239	285

Table 5. Summary of the results of simulation tests of equivalent stress σ_{eq} changes in the shaped pipe section resulting from deformations caused by bending

Model symbol	Equivalent stresses in the pipe on the outer side of the wall compressed in the vertical direction $\sigma_{eq\ ovc}$	Equivalent stresses in the pipe on the inner side of the wall compressed in the vertical direction	Equivalent stresses in the pipe on the inner side of the wall tensioned in the vertical direction	Equivalent stresses in the pipe on the outer side of the wall tensioned in the vertical direction $\sigma_{eq\ ovt}$	Equivalent stresses in the pipe on the outer side of the wall in the horizontal direction $\sigma_{eq\ oh}$	Equivalent stresses in the pipe on the inner side of the wall in the horizontal direction
	MPa					
MW	297	289	305	380	277	275
M1	172	162	226	206	199	239
M2	185	203	208	252	236	244

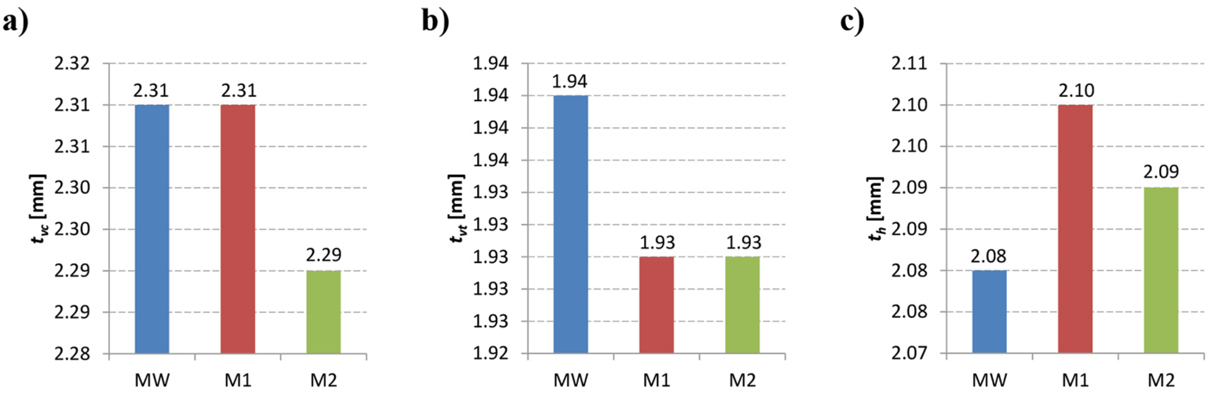

Figure 22. Thickness values of the bent pipe wall: a) in the vertical direction on the compressed side, b) in the vertical direction on the tensioned side, c) in the horizontal direction

case under consideration must not exceed 10%. In view of the slight changes in pipe diameter observed during mechanical bending using a flexible mandrel, depending on the angle of the cross-section of the bent pipe arc, and considering the recommendations of the standards, the evaluation focused on the ovalisation of the cross-section located exclusively at an angle of 45° (Figure 26). The results of this evaluation are presented in Table 6. Calculated

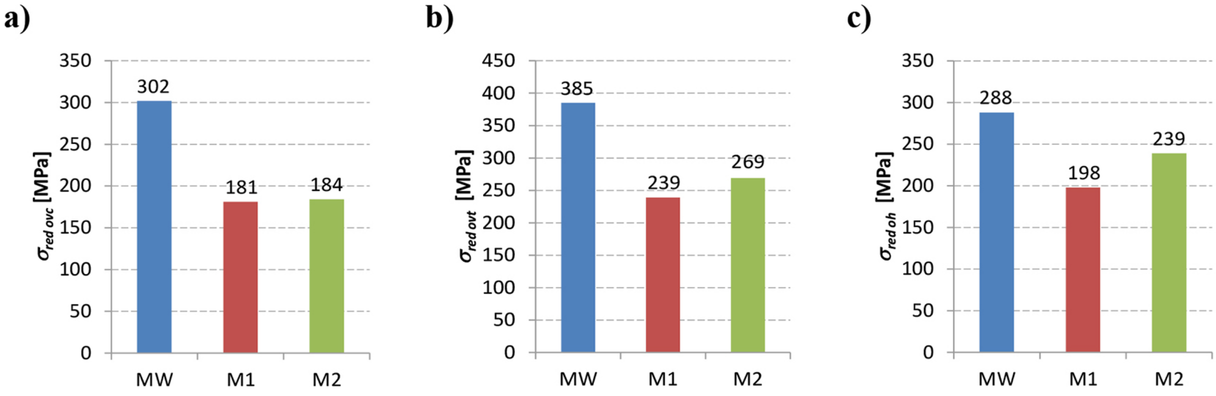

Figure 23. Reduced stresses values on the outer side of the bent pipe wall: a) in the vertical direction on the compressed side, b) in the vertical direction on the tensioned side, c) in the horizontal direction

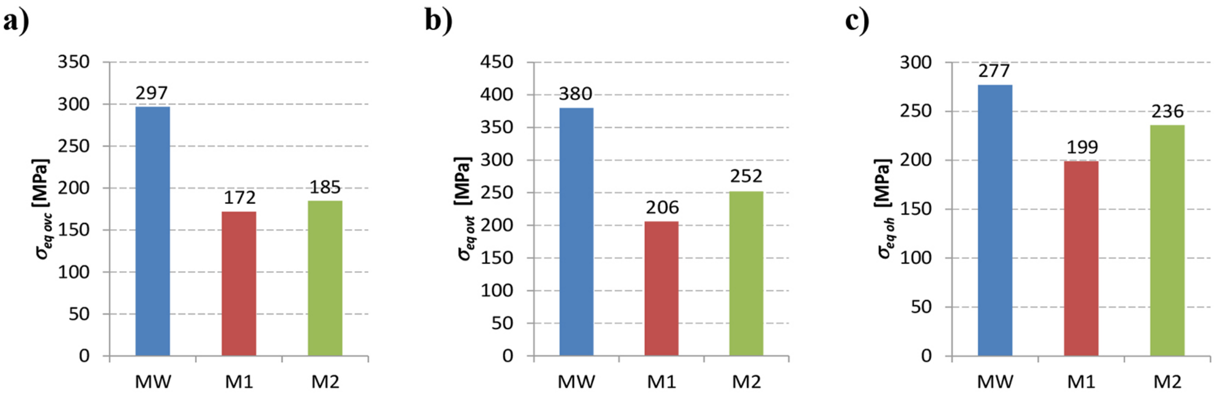

Figure 24. Equivalent stresses values on the outer side of the bent pipe wall: a) in the vertical direction on the compressed side, b) in the vertical direction on the tensioned side, c) in the horizontal direction

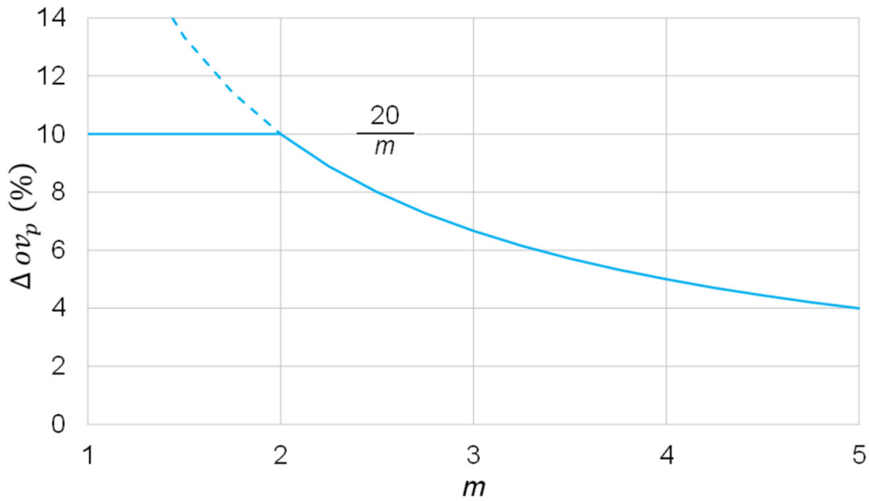

Figure 25. Course of permissible ovalisation Δov_p as a function of the *m* coefficient (prepared based on the EN 13480-3 standard [16])

based on Equation 3, the ovalisation values Δov for bending a pipe without the mandrel are 6.618% for the outer diameter and 7.994% for the inner diameter. Bending without a mandrel therefore results in the permissible ovalisation value being exceeded, which for the assumed outer diameter D_o = 32 mm and bending radius R = 84 mm is 7.619%, (Figure 25). The use

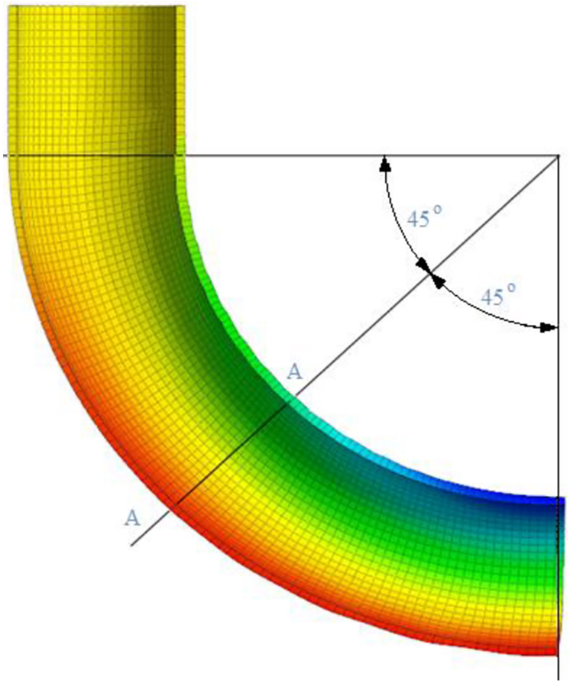

Figure 26. Location of the cross-section used for ovalisation evaluation

Table 6. Ovalisation values Δ*ov* for a pipe cross-section positioned at an angle of 45°

Model symbol	Δov (%)	
	Outer diameter of the pipe	Inner diameter of the pipe
MW	6.618	7.994
M1	0.187	0.360
M2	0.000	0.072

of the flexible mandrel with segments spaced at 2 mm intervals allows the ovalisation to be reduced to 0.187% for the outer diameter of the pipe and to 0.360% for the inner diameter of the pipe. Reducing the distance between segments to 1 mm guarantees complete elimination of ovalisation in the case of the outer diameter of the pipe, while in the case of the inner diameter of the pipe, it reduces ovalisation to 0.072%.

CONCLUSIONS

The paper presents a proposal for a new flexible mandrel and the results of preliminary model tests of its design carried out using FEM. These results included an analysis of deformations and stresses in a thin-walled pipe bent at an angle of 90°. The bending of a P265GH steel pipe with an outer diameter of 32 mm and a wall thickness of 2.1 mm was analysed. The bending radius was 84 mm. The above conditions are characteristic of pipes requiring the use of a mandrel during bending. Three bending variants were tested: without the use of a mandrel and with a mandrel with segments spaced 2 mm and 1 mm apart. In the bending version without a mandrel, significant ovalisation of the pipe cross-section was observed. The ovalisation was 6.618% for the outer diameter of the pipe and 7.994% for the inner diameter of the pipe, respectively. Significant reduced stresses of 385 MPa also occurred in the tensioned zone. The introduction of the flexible mandrel significantly reduced the stress values. For a segment spacing of 2 mm, the reduced stresses dropped to approximately 239 MPa, and for a spacing of 1 mm to 269 MPa. The stresses thus decreased by more than 35% compared to bending without a mandrel. Ovalisation using the mandrel with segments spaced 2 mm apart was only 0.187% for the outer diameter of the pipe. With segments spaced 1 mm apart, ovalisation was completely eliminated ($\Delta ov = 0\%$).

The cross-sectional shape resulting from the pipe bending process remained almost perfectly circular, both in terms of its external and internal diameter. The use of the mandrel further reduced the differences in wall thickness between the compressed and tensioned sides. Bending with the mandrel limited local deformations and flattening of the pipe. It was determined that the correct selection of the spacing between the segments has a key impact on the even distribution of stresses. Simulations confirmed the required radial stiffness while maintaining the bending flexibility of the mandrel. After removing the mandrel, the elastic deformations decreased, which facilitated its removal from the pipe. The geometric parameters after bending were within the normative limits [14–17].

The results of the tests conducted allow to conclude that the use of the proposed flexible mandrel in the thin-walled pipe bending process significantly improves the quality of the shaped element. The flexible mandrel stabilises the pipe cross-section, preventing ovalisation and flattening. This reduces the risk of defects such as corrugations, wrinkles or wall cracks. The mandrel allows the correct cross-sectional dimensions to be maintained, even for small bending radii. It reduces the stresses in the material, which improves the strength and durability of the bent section. It ensures an even distribution of stresses in both the tensioned and compressed layers of the pipe. The mandrel design with spiral spring armour and flexible cord braiding combines radial stiffness with flexibility. Removal of the mandrel after bending is easy thanks to the threaded end and extractor. The proposed solution does not require specialised and expensive mandrel bending machines, which reduces production costs.

Bending using a specially designed flexible mandrel can be used for bending angles up to 90° and for pipes with an external diameter of up to 50 mm. Optimising the spacing between mandrel segments further improves bending quality and reduces deformation. The bending method using the proposed mandrel increases the repeatability of the production process, which is crucial in industrial pipe manufacturing. Maintaining the standard ovalisation of the cross-section improves the stability of the medium flow in pipelines and their operation. The reduction of elastic stresses after bending allows for better dimensional control and easier mandrel removal. The introduction of the proposed flexible mandrel improves the overall quality of pipeline products in accordance with standards [14–17,71]. This eliminates the need for costly heat treatment to relieve stress after bending. The mandrel is compatible with traditional cold bending equipment. Its design is particularly useful for bending pipes with thin walls and small radii of curvature. The bending technology using the proposed mandrel can complement or replace existing mandrel bending methods.

Simulation tests have demonstrated the accuracy of the proposed flexible mandrel design. The results of the tests also justify the assumption that its design significantly increases the efficiency, precision and durability of the thin-walled pipe bending process. At the same time, high dimensional accuracy is maintained and excessive stresses in the shaped section of the pipe are eliminated. Experimental validation of the bending process using the proposed mandrel is planned, and its results will be published in separate papers.

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