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Effect of Flower Pattern on The Curvature of High-Strength Steel Pipe in Roll Forming

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Abstract

The geometrical characteristic of products is one of the crucial quality indicators in the cold roll forming process. In this process, an appropriate flower pattern for rolls is vital to achieve the desired geometry and quality for high-strength steel pipes. In this paper, four different flower patterns, including circular, edge bending, double radius, and reverse bending are designed for the roll forming process of the high-strength steel pipe. Then, the effect of the flower pattern on the curvature distribution of the deformed strip is investigated using finite element analysis. The accuracy of the finite element model is evaluated by performing experimental tests. The results show that forming the strip with the reverse bending flower pattern leads to a more uniform curvature distribution in its cross-section, especially in the edge portion. Thus, this flower pattern design method is recommended for the roll forming process of the high-strength steel pipes.

***Keywords*:** Cold roll forming process, Flower pattern design, Pipe curvature distribution, High strength steel, Finite element modeling

1. Introduction

In the cold roll forming process, continuous and consecutive bends are created in sheet metal by passing it through rotating rolls. In this process, the rolls provide a smooth metal flow between forming stands. Generally, the more complex the section's shape, the more steps are needed to deform the strip [1]. The deformation process takes place in 4 sections: forming section, fin-pass section, welding section, and sizing section.

The strip cross-sections in the forming stands are drawn considering a neutral axis to show the forming steps. The resulting diagram is called flower pattern. One of the most critical items in the design of the cold roll forming process is the design method of the flower pattern and the roll profiles. Four common flower patterns are used in the cold roll forming process of pipes: circular forming, edge bending forming, double radius forming, and reverse bending forming.

Kiuchi et al. [2] introduced a method that presents the rolls' profile considering some criteria, including the longitudinal strain at the strip edge to prevent wrinkling or to obtain the minimum number of stands. They [3] investigated experimentally the effect of the fin-pass sections on improving the pipe profile and presented the optimal design of fin-pass rolls. Trishevskiy et al. [4] presented the geometric parameters of the deformed strip in the roll forming process by introducing four different methods of converting the strip to a pipe. They extracted analytical relations to calculate the coordinates of different strip points and the rotation angle at different stands as a function of the initial coordinates during forming. Ona et al. [5] suggested that the number of stands in the cold roll forming process of the pipe is constant regardless of the diameter and thickness of the pipe. They offered seven stands for the breakdown section and three stands for the fin-pass section. To determine the bending angle of the pipe at each section, they assumed that a third-degree polynomial expresses the image of the pipe edge on the horizontal plane.

Moslemi et al. [6] studied the elastic-paste deformation of the strip in the cold roll forming process of the pipe by the double-radius method. They proposed an optimal design for the initial shape of the strip edge by examining the initial angle of the strip edge, the optimal contact parameters of the roll with the strip, and the fin-pass angle of rolls. Zeng et al. [7] introduced the optimal design of the roll profile in the cold roll forming process based on the surface response method. In this method, the angle and radius of rolls were chosen as the design factor, and the spring back and the maximum longitudinal strain at the strip edge were obtained as the design goal. The optimal design for the rolls' profile, the strip's cross-section in each stand, and the minimum number of stands were determined so that the wrinkling defect did not occur at the strip edge. Brunet et al. [8] created a finite element code to simulate the production process of various products, including pipes. They compared the geometry of the deformed strip and the strain distribution with the experimental data and observed a good agreement.

Abeyrathna et al. [9] presented a new geometrical method for the flower pattern by comparing three different flower patterns and suggested that the reduction of the longitudinal strain in the final stands leads to fewer defects. They used the optimal model reported by Walker et al. [10] to generalize the pipe roll forming method, and good adaption was observed. Karimi et al. [11] investigated the effect of flower pattern design in the cold roll forming process of ERW pipe on spring back and thickness distribution of the final product. They concluded that the reverse bending flower pattern leads to a uniform thickness distribution at the strip edge while the circular flower pattern leads to the minimum value of spring back. The effect of the flower pattern design on the curvature distribution of the final pipe has not been investigated yet. In this paper, the cold roll forming process of the pipe was simulated using MSC Marc Mentat software, and the effect of circular, edge bending, double radius, and reverse bending flower patterns on the curvature distribution of the pipe was investigated.

2.Flower pattern design

In this work, the goal product is a high strength steel pipe made from Alform 700 which has 38.1 mm diameter and 2.8 mm thickness. In the conventional roll forming process, the strip is deformed by the roll profile when it enters into each forming stand. Therefore, the design of the rolls is directly related to the deformation of the strip. In order to design the forming rolls of different stands, it is necessary to determine the cross-sections of the strip in the forming stands, which can be extracted from the flower pattern. The effective parameters in the flower pattern design are the initial strip width, the inter-stand distance, the number of stands, and the amount of deformation at each stand.

Since the cross-section of the deformed strip changes to a closed profile at the end of the process, it is essential to determine the optimal initial strip width by considering its changes during the process to achieve a pipe with precise dimensional and geometrical tolerances. The neutral axis length is used to calculate the initial strip width in the roll forming process of open profiles. However, in the roll forming process of the pipe, in addition to transverse bending, the circumferential compression in the fin-pass and sizing sections and the use of the strip in high-frequency resistance welding as a consumable material to fill the welding seam should be taken into account to determine the initial strip width. As a result, considering the geometry of the final pipe, the amount of circumferential reduction applied in the fin-pass and sizing sections, and the approximate amount of material consumed in the welding section, the initial strip width was calculated as 115 mm.

The strip deforms gradually in the space between stands. In order to reduce manufacturing costs and shorten the roll forming production line, it is more desirable to reduce the distance between the stands. On the other hand, the distance between the stands should be chosen so that it is not less than the minimum distance necessary for the free deformation of the strip. The appropriate distance between the stands is determined according to the deformation length. Deformation length is the distance along the strip length that deforms from the previous geometry to the roll profile of the next stand. Bhattacharya [12] presented an analytical equation based on minimizing deformation energy to calculate the deformation length in the roll forming of symmetrical channel profiles. Lindgren [13] showed that the deformation length increases with the yield strength, and the deformation length obtained from the simulation results is significantly different from the value calculated from the analytical equation provided by Bhattacharya. Salmani [14] performed the analytical and numerical research to predict the deformation length in the cold roll forming process of the pipe. However, there is still no equation that can predict the deformation length of in this process. In this paper, the inter-stand distance was determined to be 300 mm for the side roll stands and 400 mm for the other stands based on the finite element simulation which is explained in the following section.

According to Ona et al. [5], four breakdown stands, three side roll stands, and three fin-pass stands were considered. Figure 1 shows the forming rolls considered in the roll forming process of the pipe. The welding and sizing rolls placed after the forming stands are not included in the flower pattern design.

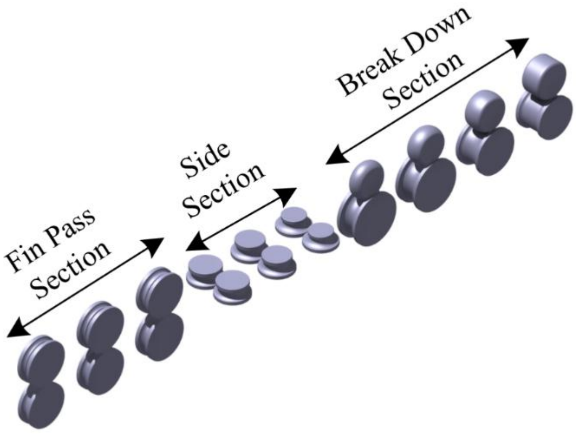

Figure 1 Schematic representation of the forming rolls.

In the next step, the amount of deformation in each stand should be determined. According to Ona et al. [5], the edge position of the strip along the production line was approximated as a third-degree polynomial. Figure 2 shows the curve passing through the strip edge at each stand.

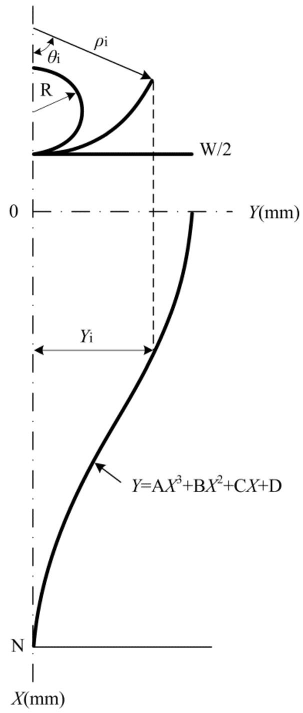

Figure 2 The curve passing from the strip edge at each stand [5].

Where x is the longitudinal direction along the forming path from the last pinch roll stand, y is the transverse direction along the cross-section of the strip, Y_i is the distance of the strip edge to the symmetry axis of the section, ρ_i the curvature radius of the strip, θ_i the deformation angle, R is the final radius of the pipe, and W is the initial strip width. Since ten stands were considered for all the flower patterns, the curve mentioned is the same for all the design methods. Equation 1 represents the third-degree polynomial obtained for the flower pattern design for an initial strip width of 115 mm and ten stands.

$y=0.0864x^3-1.4256x^2+57.500$ (1)

In fin-pass stands, a certain amount of circumferential compression is applied to the edge portion of the strip. It improves the geometry of the pipe in terms of curvature and thickness distribution. Also, a proper fin angle in the fin-pass stands should be considered to improve the edge angle of the deformed strip. The values of circumferential compression and the angle of the fin-pass roll were selected according to Kiuchi'ssuggestion [3] which are listed in Table 1.

Table 1 Fin angle and circumferential compression in the fin-pass sections.

Fin-pass stand	Fin-pass angle (°)	Circumferential compression (%)
1	20	0.8
2	10	0.5
3	5	0.3

The cross sections of the deformed strip were determined in the forming stands based on the different design methods. Figure 3 shows the flower patterns designed for the roll forming process of the pipe.

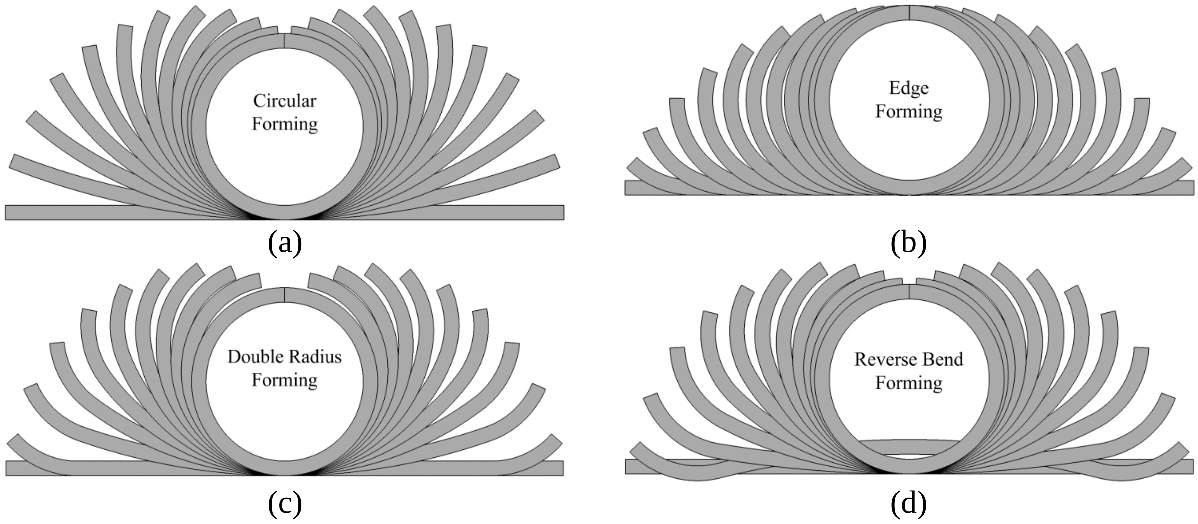

Figure 3 Flower patterns designed based on the different methods: a) circular, b) edge bending, c) double radius and d) reverse bending.

3. Finite element modelling

In order to model the roll forming process of the pipe with a 38.1 mm diameter, first, the flower patterns were sketched, then each forming roll was modeled in the Catia software and imported into the MSC Marc Mentat software. In the design of the roll forming process, downhill forming was not used, and the strip moves along a straight line and at a constant height from the beginning of deformation to the last stand [15]. The complete model of the cold roll forming process of the pipe using the reverse bending flower pattern is shown in Figure 4. Due to the long strip length, three pairs of pinch rolls were used to prevent the strip deviation before the forming stands.

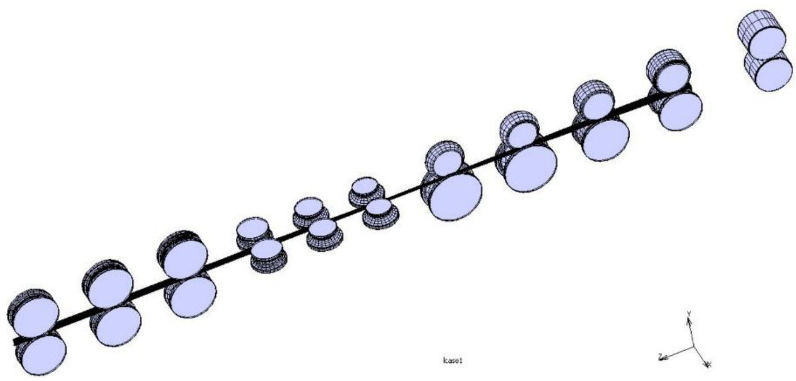

Figure 4 Finite element model of the roll forming process

The rolls of the breakdown and fin-pass sections were drivers while the pinch and side rolls were idlers. The breakdown rolls form the middle portion of the strip so that at the end of this section, the bending angle of the pipe reaches 90 degrees. When the bending angle exceeds 90 degrees, side rolls with a vertical axis are applied. The last forming section is the fin-pass section, in which the defects in the deformed strip are significantly corrected, and the strip is ready to enter the welding section.

The cold roll forming process was simulated in the commercial software MSC Marc Mentat. The geometrical characteristics and mechanical properties of Alform 700 series, which is a high-strength steel, are summarized in Table 2. It should be noted that Poisson's ratio is 0.3, and the yield strength is calculated using the 0.2% strain rule.

Table 2 Geometrical characteristics and mechanical properties of the strip.

Geometrical characteristics	Value	Mechanical properties	Value
Strip length (mm)	3600	Yield strength (MPa)	630
Strip width (mm)	115	Ultimate tensile strength (MPa)	820
Strip thickness (mm)	2.8	Uniform elongation	0.16

Due to the symmetry in the circular cross-section, only half of the strip was modeled, and the symmetry constraints were applied in the middle section of the strip. The strip was defined as a deformable part and discretized with solid elements in three layers through the thickness. Isotropic behavior and isotropic hardening were assumed for the material. The true stress -strain curve was defined as shown in Figure 5. Since the deformation of the roll is very small compared to the strip, rolls were introduced as rigid bodies. The rolls were rotated in a fixed position, and Coulomb's law was considered with a friction coefficient of 0.2. The speed of the strip movement in the simulation was 9 m/min.

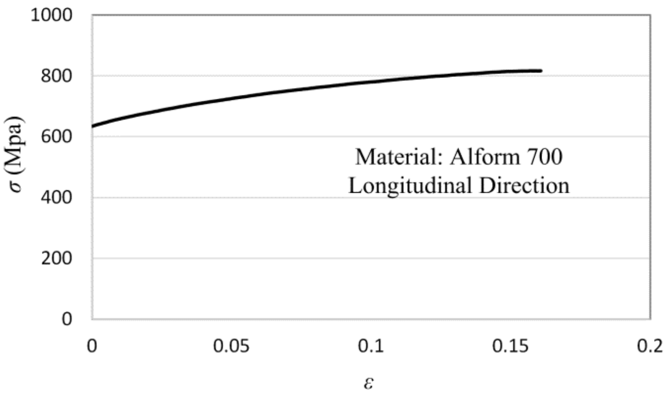

Figure 5 The true stress-strain curve of the Alform 700.

4.Results and discussion

In order to verify the finite element model, the curvature radii predicted for the deformed strip were compared with the experimental ones. According to Figure 6, the curvature radius of the deformed strip was measured in the eleven cross-sections along the strip length with distances of 100 mm.

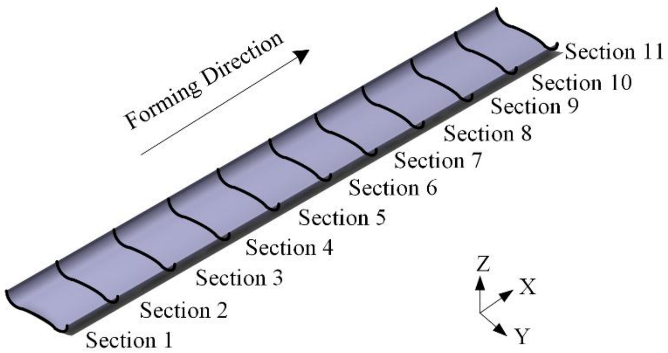

Figure 6 The transverse cross-sections used for measuring the curvature radius of the deformed strip.

The rolls were designed by the flower pattern of the reverse bending in the experimental tests. Therefore, the edge section, with an arc length of 18.5 mm on both sides, has a different curvature radius than the middle portion. In the middle portion, a hypothetical circle passing through the three beginning, end, and center points of this portion was considered, and the curvature radius (R_1) is assumed to be equal to the circle radius. The curvature radius of the edge portions (R_2) was also calculated by considering three points from the beginning, end, and center of this portion and passing the circle through these three points. Then, the curvature radius of the edge portion was considered equal to the average curvature radius of the right and left sides of the strip. According to the repetition of the experimental tests, the average of the measured values was used in the results. Figure 7 shows the method of choosing points and the curvature radius of the middle and the edge portions of the deformed strip.

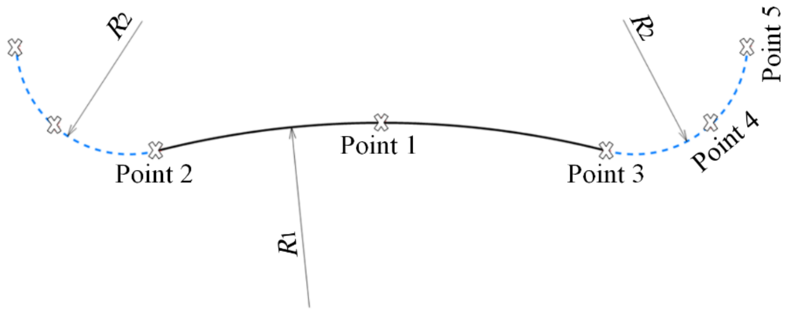

Figure 7 The method of measuring the curvature radius of the middle and the edge portions of the deformed strip.

As mentioned, the curvature radii of the middle and edge portions were calculated for the finite element simulations and compared with the experimental results. Figure 8 shows the curvature radius for the eleven sections. As seen, there is a good agreement between the numerical and experimental results that verifies the accuracy of the finite element model. However, the difference in the middle portion of the profile is slightly more than its two ends.

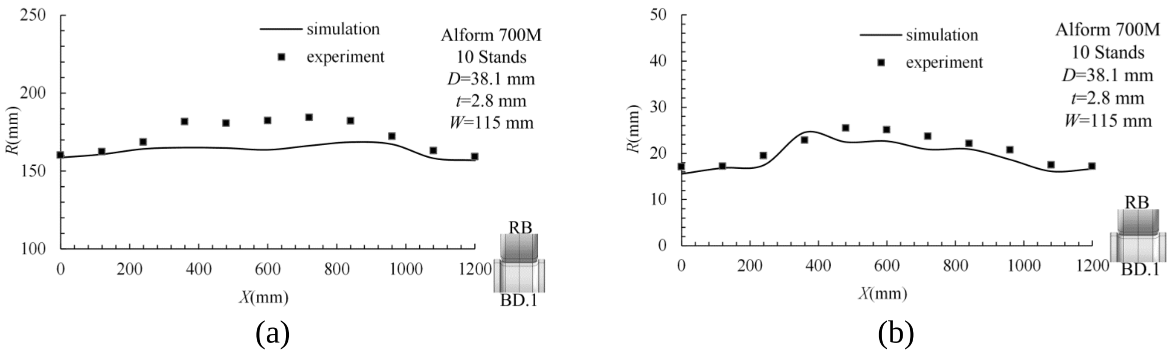

Figure 8 Comparison of the curvature radii of the deformed strip obtained from the numerical simulations and the experimental tests for (a) the middle portion and (b) the edge portion.

To investigate the curvature changes in the cross-section of the strip, the dimensionless factor of relative curvature was defined as the ratio of the deformed strip's curvature to the final pipe's curvature [15]. When the relative curvature approaches one and has a uniform distribution, the product profile is close to the final pipe. However, the relative curvature close to zero indicates a low deformation. According to Figure 9, the curvature was calculated using MATLAB software, whose input is the coordinates of the nodes, and the output is the curvature of the strip. The strip curvature was calculated by having the coordinates of the nodes and passing a circle through each three consecutive points.

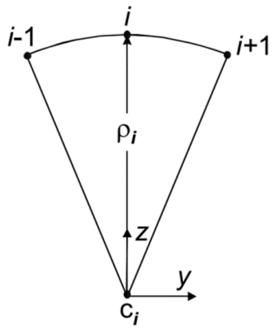

Figure 9 The method of measuring the curvature radius from the coordinates of the nodes.

Figure 10 shows the distribution of the relative curvature at the deformed strip in the last stand of breakdown and side roll sections. In the breakdown section, the cross-section is uniformly deformed in the circular flower pattern, while the edge portion is strongly deformed and its curvature radius reaches one in the other flower patterns. As seen, in the side roll section, the middle portion of the strip undergoes deformation and takes about 75% of the final curvature radius. However, in the edge bending method, a part of the cross-section close to the center of the cross-section is slightly deformed since the deformation starts from the edge and gradually continues to the center.

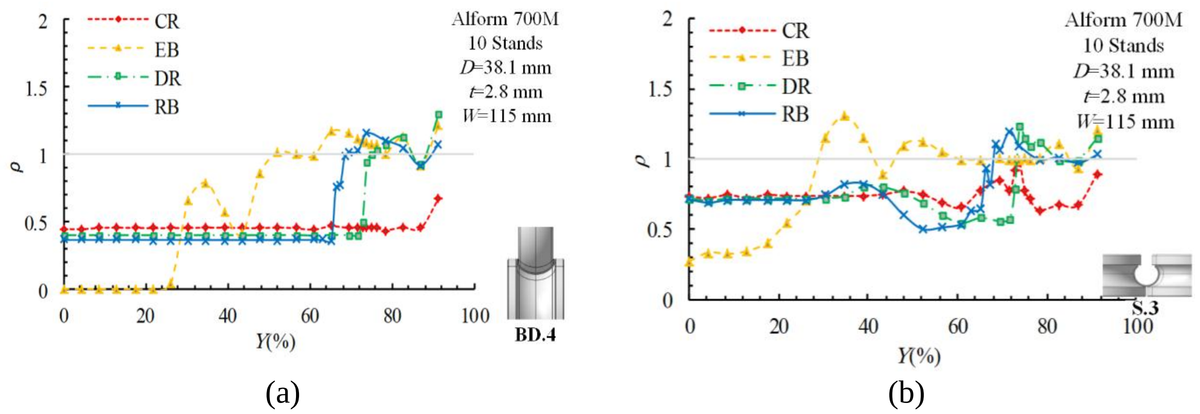

Figure 10 Distribution of the relative curvature at the half of the deformed strip in the last stand of (a) breakdown and (b) side roll sections.

In the side roll section, although the middle portion of the strip is deformed, and the non-bending areas of the strip gradually decrease, the non-uniformity of the curvature distribution remains. The circumferential compression applied in the fin-pass section leads to complete contact of the strip's outer layer with the fin-pass rolls. As a result, the average relative curvature of the deformed strip increases and approaches one (see Figure 11). In addition, similar to [16, 17], the curvature distribution becomes more uniform. Thus, the portions with less or more curvature than one are corrected by passing through the rolls of the fin-pass section.

According to Figure 11, it can be seen that at the end of the fin-pass section, the relative curvature of center portion for all the flower patterns is close to one and, therefore, has a desired condition. As a result, the difference between methods should be find in the relative curvature of the middle and the edge portions. In these portions, the double radius and reverse bending methods provide a relative curvature close to one, while the circular and edge bending methods cause fluctuations and incomplete curvature. The slight fluctuations can be also seen in the near area of the edge for the double radius method. The average relative curvature of the deformed strip and its deviation in the third fin-pass stand for the different design method were summarized in Table 3. As seen in Table 3, the reverse bending method has an average relative curvature of 0.97 and a deviation of 0.02 that shows a better performance compared to the other method. It can be concluded that the best method for designing the flower pattern of a high strength steel pipe is the reverse bending method.

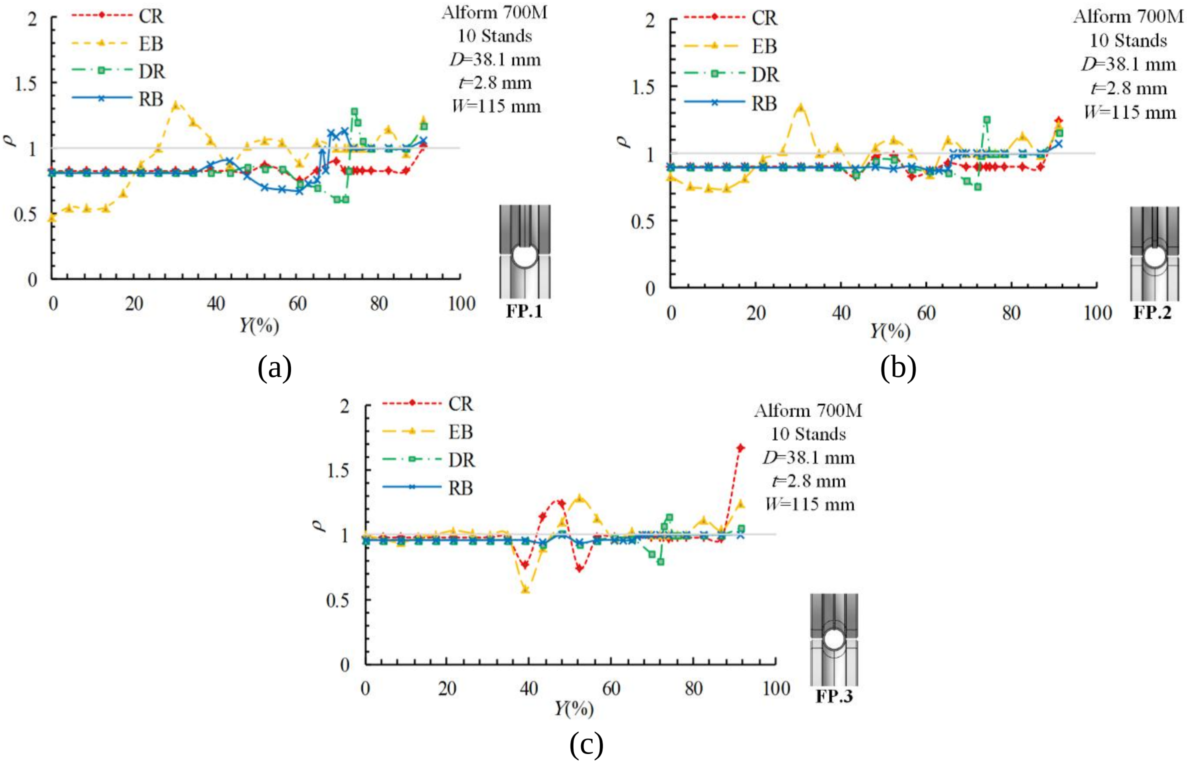

Figure 11 The relative curvature distribution of the deformed strip at the (a) first, (b) second, and (c) third fin-pass stands.

Table 3 The average relative curvature of the pipe at the third fin-pass stand.

Flower pattern	Circular	Edge bending	Double radius	Reverse bending
Average relative curvature	1.00	1.00	0.96	0.97
Deviation of average relative curvature	0.16	0.12	0.06	0.02

7. Conclusions

In this paper, the cold roll forming process of high-strength steel pipe was numerically and experimentally investigated. The flower pattern of the forming stands was designed using the circular, edge bending, double radius, and reverse bending method. The results showed the relative curvature of the center portion of the deformed strip is close to one for all the flower patterns at the end of the fin-pass section. However, the relative curvature at the middle and edge portions has some fluctuations for the circular and edge methods, while not only this is not seen for the other two methods but also, they have a relative curvature close to one. In the area near the edges, although the double radius method shows a minor variation, the reverse bending method presents the best curvature distribution and the least deviation. Thus, finally, the reverse bending method is suggested to produce high-strength steel pipes by the cold roll forming process.

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