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ORIGINAL ARTICLE

Control strategy of multi-point bending one-off straightening process for LSAW pipes

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Abstract At present, the straightening process for longitudinally submerged arc welding (LSAW) pipes is a three-point bending multi-step straightening method. In the process, the straightness of the overall pipe length requires to be measured prior to each single straightening operation, and the determination of the straightness parameters mainly relies on the operator's experience. All of this has resulted in low efficiency of the current process. In this paper, a quantitative method is firstly established to calculate the theoretical straightening moment according to a pipe's initial deflection distribution, which is based on the springback equation of small curvature plane bending previously developed. The multi-point bending one-off straightening control strategy is then developed, along with the method for obtaining corresponding straightening parameters by discretizing and linearizing the theoretical moment curve. The finite element methods (FEM) simulation results from the LSAW pipe indicate the more number of pressure points, the higher the straightening accuracy. To reduce the number of pressure points and ensure the straightening accuracy, the concept of the load correction coefficient is introduced, and the method to obtain an optimal correction coefficient is then excessively studied. Feasibility and reliability of the newly developed control strategy is verified through a FEM simulation model. Furthermore, the FEM simulation model is validated by physical simulation experiments of small-sized pipes. The FEM simulation results indicate that by using the newly developed control strategy with an optimal load correction coefficient, a LSAW pipe with an initial deflection of 70.89 mm could be modified into the one with a maximum residue deflection of 8 mm or less in one round of straightening operation, when numbers of the pressure points are set up as 3, 4, 5, and 6, respectively, so that the straightness can be obtained within 0.065 % to far less than the standard requirement of 0.2 %.

Keyword Pipes · Bending · Pressure straightening · Quantitative control

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1 Introduction

The straightness is an important indicator in measuring the quality of a longitudinally submerged arc welding (LSAW) pipe. In the LSAW manufacturing process, there often arises a demand to straighten the end of LSAW pipes because they fail to meet the overall straightness requirements, due to the influence of such factors as the welding thermal stress, the forming equipment, and the overall straightness of the mould [1–3].

According to the geometric particularity of the LSAW pipes, the pressure straightening method tends to be applied at present by many manufacturers to correct straightness of the pipes. The pressure straightening method, also known as the three-point over-bending straightening, is to place the metal workpiece that is with an initial deflection onto between the two adjustable supporting points, then to apply a load in the opposite direction at the point with the maximum deflection, and consequently to make the workpiece straight, following the reverse bending [4]. For a long time, the execution of the pressure straightening process mainly relied on operators to determine the straightening stroke, based on their experience and estimation through repeated measuring and testing. Therefore, this traditional approach could not meet the elevated needs from the market, due to its low straightening efficiency and high intensity of labor, as well as an uncertainty of the straightening accuracy.

In recent years, many scholars in different countries have gotten involved in the research of the pressure straightening process. Katoh and Urata [5] from Japan have developed the load-deflection model for the three-point bending single-step pressure straightening process, in which the quality of straightening has been intentionally controlled by predicting the quantity of springback. Kim and Chung [6] from Korea, who were inspired by the load-deflection model, have made the automatic straightening of rack bars possible through the online identification module of various material characteristics and the fuzzy self-learning controller system. Zhai [7] from China has proposed an approach to work out the straightening stroke that is required in the single-step straightening, by applying curvatures in the straightening process and modifying the Ramberg–Osgood elastic–plastic equation. Ling et al. [8] from China have proposed an improved straightening stroke-deflection model according to the load-deflection model; however, lots of experimental data are required in the new method to figure out the expression formula for stroke prediction.

Due to limitations on the current three-point bending pressure straightening process, one single-step straightening can only straighten the pipe from a big single-curvature curve into a small double-curvature curve in the shape of the letter "S." One single-step strengthening would work efficiently for pipes of which the initial deflection is relatively small, but when the initial deflection of a pipe is big enough, the multi-step straightening process would be required to achieve the goal for the improved overall straightness on the pipe. Since the deflection distribution over the pipe length needs to be measured prior to each single-step straightening in order to determine the parameters such as the load position, the support location, and the straightening stroke, etc., the multi-step straightening process is too slow to satisfy the requirements of the industry.

To overcome the deficiencies on the existing straightening process, this paper proposes a control strategy for the multi-point bending one-off straightening process, based on the theoretical straightening moment. The quantification of this control strategy could provide a theoretical basis to the design and application of an automatic straightening machine for LSAW pipes.

2 Theoretical straightening moment of the pipe

Plane bending is defined as "when the entire external forces act on the beam in the vertically symmetrical plane, the beam axis after deformation will be located in the symmetrical plane" [9]. As the deformation of a LSAW pipe is characterized by the deflection curve being within the identical plane, and the straightening process is similar to that of the curve beam reverse bending, the straightening of the LSAW pipe could be analyzed in terms of the springback equation of small curvature plane bending. The concept of an initially equivalent strain ε_0 has to be introduced first [9]: it is assumed that there exists a linear distribution of the initial strain ε_0 in the studied curve micro-beam, related to a straight beam, and

$$\varepsilon_0 = K_0 w \tag{1}$$

where K_0 is the initial curvature of the micro-beam, and w is the distance from the neutral axis when uvw is selected as the cross-section coordinate system, with the coordinate origin being at the centroid of the cross section of the micro-beam, as shown in Fig. 1.

Furthermore, based on the springback equation of small curvature plane bending [9], the geometric constraint equation and the springback equation in the case of the pure reverse bending can be expressed as two unified formulas, namely,

$$K_p = K + K_e - K_0 \tag{2}$$

$$K_p = K - \frac{M}{EI} \tag{3}$$

where M is the loading moment, which is defined as positive when it causes the straight beam to protrude in the positive direction of w axis, and otherwise negative; K is the curvature of the center layer of the cross section after being loaded; K_e is the curvature of the equivalent strain of the neutral layer when the loading moment M_e has been imposed on the pure elastic body; and K_p is the final curvature of the center layer of the cross section after springback; A curvature is defined as positive when it is in the same direction as the acted loading moment, and otherwise negative; E is the elastic modulus; and I is the sectional moment of inertia.

On the basis of assumptions in the springback theory for the small curvature plane bending and definition for the initial equivalent strain, when the loading moment M affects on the hollow circular cross section of a curved beam, the strain ε can be expressed as

$$\varepsilon = (K - K_0) w \tag{4}$$

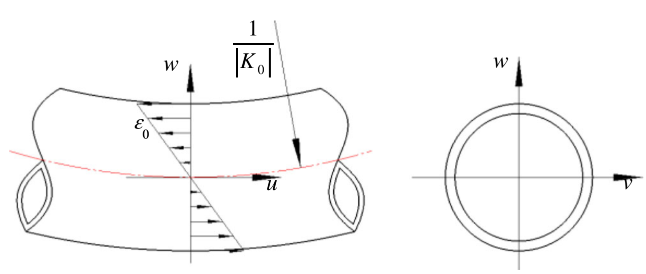

Fig. 1 The cross section and coordinate of the curved micro-beam

The stress–strain relationship for the elastic–plastic materials is expressed as $\sigma = f(\varepsilon)$, and according to the balance condition of section load, the moment M is given by

$$M = \int_A \sigma \cdot w \mathrm{d}A = \int_A f[(K - K_0)w] \cdot w \mathrm{d}A \tag{5}$$

where A is the area of the hollow circular cross section.

Since the pressure straightening process pertains to the issue of a small elastic–plastic deformation, the bilinear hardening material model can be applied to secure a high degree of accuracy in both the elastic stage and the plastic stage. The material model can be expressed as follows:

$$\begin{cases} \sigma = E\varepsilon & \varepsilon \le \varepsilon_s \\ \sigma = \sigma_0 + D\varepsilon & \varepsilon > \varepsilon_s \end{cases} \tag{6}$$

and

$$\sigma_0 = \sigma_s \left(1 - \frac{D}{E}\right) \tag{7}$$

where E is the elastic modulus, D the plastic tangent modulus, σ_s the material initial yield stress, σ_0 the intercept stress, and $\varepsilon_s = \frac{\sigma_s}{E}$ is the elastic limit strain.

In the process of straightening a pipe, the curved micro-pipe undergoes the elastic–plastic deformation bent over in the reverse direction under effect of the loading moment M. From a close examination of the geometry of a cross section shown in Fig. 2, when the distance between the elastic–plastic boundary and the neutral axis is denoted as w_s, the angle θ_s can be expressed as $w_s = R_m \sin\theta_s$, then

$$\sin\theta_s = \frac{\varepsilon_s}{(K - K_0)R_m} \tag{8}$$

where $R_m = R_1 - \frac{t}{2}$ is the intermediate radius, t is the thickness of the pipe, and $R_1$is the external radius.

As mentioned previously, the position of the elastic–plastic boundary (θ_s) primarily controls the determination of the bending moment. M_s is defined as the elastic ultimate moment that equals to the loading moment when $\theta_s = \frac{\pi}{2}$, and it is given by

$$M_s = \frac{\sigma_s \cdot I}{R_m} \tag{9}$$

When a loading moment is less than M_s, the curved micro-pipe will spring back to its initial state after unloading.

When a loading moment passes M_s, the analytical expression of the elastic–plastic bending moment can be obtained by substituting Eq. 6 for Eq. 5, then

$$M = \frac{1}{\pi}(E - D)I(K - K_0)(2\theta_s - \sin 2\theta_s) + 4\sigma_0 R_m^2 t \cos\theta_s + DI(K - K_0) \tag{10}$$

where I is the moment of inertia of the hollow circular section and is given by $I = \pi R_m^3 t$. Using this in Eq. 10, then

$$\frac{M}{EI} = \frac{D}{E}(K - K_0) + \frac{(K - K_0)}{\pi}\left(1 - \frac{D}{E}\right)(2\theta_s + \sin 2\theta_s) \tag{11}$$

If the curved micro-pipe is bent over in the reverse direction by the loading moment M, then the final curvature of the center layer of the cross section becomes 0 following unloading, namely, the curved micro-pipe is completely straightened by this loading moment, where $K_p = 0$. So the springback Eq. 3 can be expressed as

$$K = \frac{M}{EI} \tag{12}$$

Hence, as known from Eqs. 11 and 12, the expression of K, the curvature of the center layer of the cross section when loading, is written as

$$K = \frac{D}{E}(K - K_0) + \frac{(K - K_0)}{\pi}\left(1 - \frac{D}{E}\right)(2\theta_s + \sin 2\theta_s) \tag{13}$$

When the value of the initial curvature of the curved micro-pipe K_0 is obtained, by applying Eq. 13, the value of K could be obtained through the numerical iteration method. By applying the values of K_0 and K into the Eq. 11, the theoretical straightening moment M that can straighten the curved micro-pipe is completely calculable.

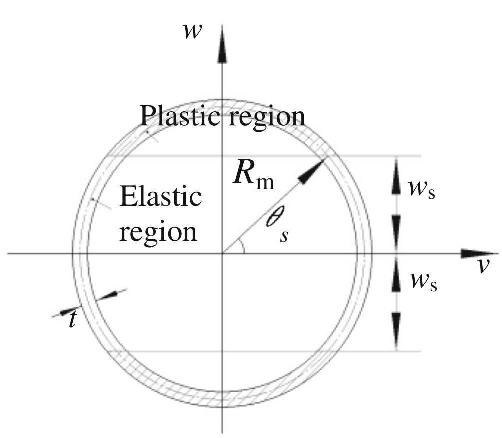

Fig. 2 The cross-section characters of the curved micro-pipe

Fig. 3 Measuring site of the straightness-offgrade LSAW pipe

Table 1 Geometric characteristics of LSAW pipe

Pipe No.	Length/mm	Initial deflection/mm	External diameter/mm	Thickness/mm
LJ23-1	12213	70.89	457.2	12.7

3 Example for the theoretical straightening moment

As shown in Fig. 3, a straightness-offgrade LSAW pipe is on the production line. Deflection distributions of the three deflected LSAW pipes have been measured by using the 3000iTM portable coordinate measuring instrument that possesses a measurement accuracy of 0.01 mm, which is manufactured by CimCore in the USA. The measurement results have shown that all three pipes have very similar deformation characteristics, so the pipe with the ID No. LJ23-1 has been chosen as the example, with its geometric characteristics and material parameters shown in Tables 1 and 2.

By analyzing deformation characteristics of the typically deflected LSAW pipes, it is known that the deflection distribution in certain areas around two ends of the pipe is approximately linear, while the distribution in the middle area is a single-peak curve. Therefore, the piecewise polynomial curve fitting method can be used to fit the metrical data, as shown in Fig. 4, and the piecewise functions can be given as follows:

$$f_1(x) = a_0 + a_1 x \qquad x \in [0, x_l] \tag{14}$$

$$f_2(x) = \sum_{i=0}^{n} b_i x^i \qquad x \in [x_l, x_r] \tag{15}$$

$$f_3(x) = c_0 + c_1 x \qquad x \in [x_r, l] \tag{16}$$

where x_l is the intersection point of $f_1(x)$ and $f_2(x)$; x_r is the intersection point of $f_3(x)$ and $f_2(x)$; and l is the length of the pipe.

The following relations should be respectively satisfied at all intersection points:

1. The curve is continuous, then

$$\begin{cases} f_1(x_l) = f_2(x_l) \\ f_2(x_r) = f_3(x_r) \end{cases} \tag{17}$$

Table 2 Material parameters of LSAW pipe

Material	E/GPa	D/MPa	σ_s/MPa
A516Gr60	200	1833.3	345

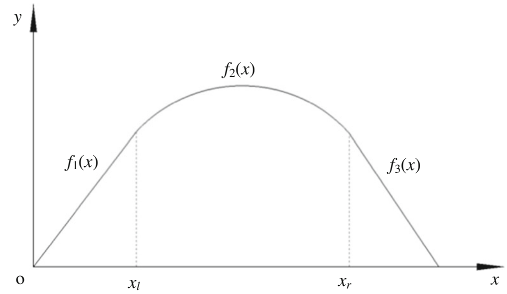

Fig. 4 The diagram of piecewise curve fitting method

2. The derivative is continuous, then

$$\begin{cases} f_1'(x_l) = f_2'(x_l) \\ f_2'(x_r) = f_3'(x_r) \end{cases} \tag{18}$$

3. The curvature is continuous, then

$$\begin{cases} f_2''(x_l) = 0 \\ f_2''(x_r) = 0 \end{cases} \tag{19}$$

4. To ensure that the curvature curve is smooth, then

$$\begin{cases} f_2'''(x_l) = 0 \\ f_2'''(x_r) = 0 \end{cases} \tag{20}$$

The metrical data from the LJ23-1 pipe has been fitted with the piecewise polynomial curve fitting method, for n=8, and thus, the corresponding coefficients of three polynomial functions are a_0=−1.639, a_1=0.0144; b_0=−13.06, b_1=0.039, b_2=−2.15×10^{-5}, b_3=9.65×10^{-9}, b_4=−2.47×10^{-12}, b_5=3.70×10^{-16}, b_6=−3.31×10^{-20}, b_7=1.63×10^{-25}, b_8=−3.37×10^{-29}; c_0= 197.4, c_1=−0.0162. The fitting results are shown in Fig. 5.

According to mathematical equations of the fitting curve, the initial curvature distribution on the LJ23-1 pipe can be figured out, as shown in Fig. 6. Moreover, the theoretical straightening moment $M(x)$ can be obtained by combining Eqs. 13 and 10, as shown in Fig. 7. Observed from Figs. 6 and 7, within the region $x \in [x_l, x_r]$, the curvature is greater than 0, which indicates that this region needs to be elastic–plastic deformed by loading the moment $M(x)$ and can be completely straightened only after $M(x)$ is unloaded. Thus, the theoretical

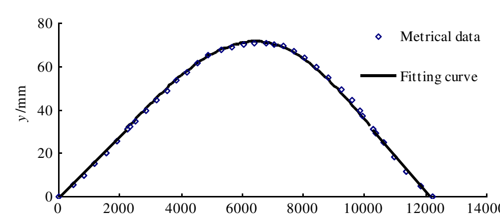

Fig. 5 The deflection distribution of LJ23-1 pipe

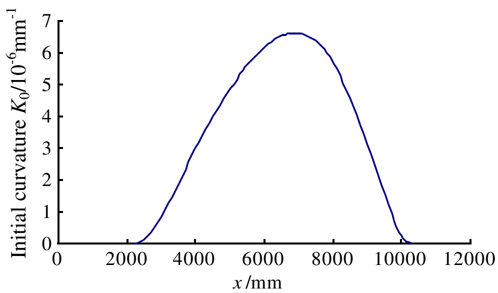

Fig. 6 The curvature distribution of LJ23-1 pipe

straightening moment in this region is greater than the elastic ultimate moment M_s. While in the region $x\in[0,x_l]\cup[x_r,l]$, the initial curvature equals to 0, so this region does not need to be straightened, and the moment $M(x)$ for this region could be any values that are less than M_s.

4 Control strategy of the multi-point bending one-off straightening process

As shown in Fig. 7, the theoretical moment of straightening a LSAW pipe is a smooth curve, which can be theoretically imposed on the axial cross section to have the pipe straightened completely in one go. Yet, in the practical manufacturing, there is not a process available to load this kind of moment directly on the pipe. So the theoretical straightening moment curve is discretized and linearized, and thus, the polygonal moment is used to approximate the smooth curve moment, as shown in Fig. 8. Observed from Fig. 8, within the region of $x\in[0,x_l]\cup[x_r,l]$, there is only elastic deformation due to loading of the straightening moment $M(x)$ being less than M_s, and the deformation would springback to the initial state after unloading.

Due to the fact that the pipes discussed and studied are small curvature pipes, the polygonal moment shown in Fig. 8 can be obtained by applying multiple concentrated forces on the overhanging beam, as shown in Fig. 9. Positions of the supporting points are $x=x_0$ and $x=x_{n+1}$. The position of a

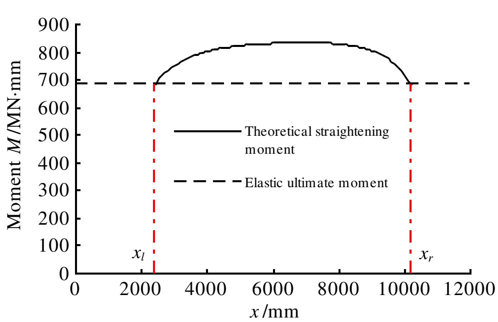

Fig. 7 The theoretical straightening moment distribution of LJ23-1 pipe

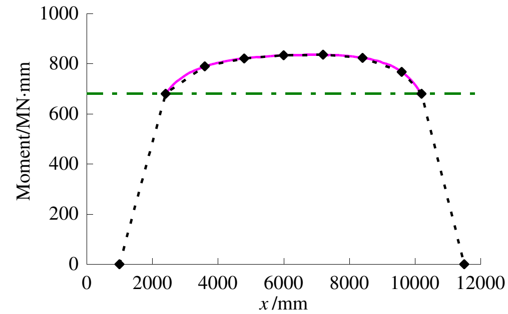

Fig. 8 Discretized and linearized the theoretical straightening moment of LJ23-1 pipe

concentrated force F_i is $x=x_i$, and value of the force can be calculated by Eq. 21.

$$F_i=-\frac{M_{i-1}}{x_i-x_{i-1}}+\frac{M_i}{x_i-x_{i-1}}\cdot\frac{x_{i+1}-x_{i-1}}{x_{i+1}-x_i}-\frac{M_{i+1}}{x_{i+1}-x_i}\quad 1\le i\le n \tag{21}$$

where the value of M_i is the corresponding theoretical straightening moment at the pressure point x_i.

Therefore, after measuring the initial deflection distribution of the pipe, the theoretical straightening moment can be obtained through putting the metrical data into the preceding theoretical formulas. Then, the method to develop the straightening control parameters for the multi-point bending straightening process is as follows:

1. Firstly, set up the position for the two supporting points that is normally near each end of the pipe;
2. Then, distribute the pressure points evenly between the two supporting points; if the number of pressure points is n, then the pressure point x_i will be

$$x_i=x_0+i\cdot\frac{x_{n+1}-x_0}{n+1}\qquad 1\le i\le n \tag{22}$$

3. By analyzing Figs. 8 and 9, the conclusion can be drawn that when the number of the pressure points is small, the

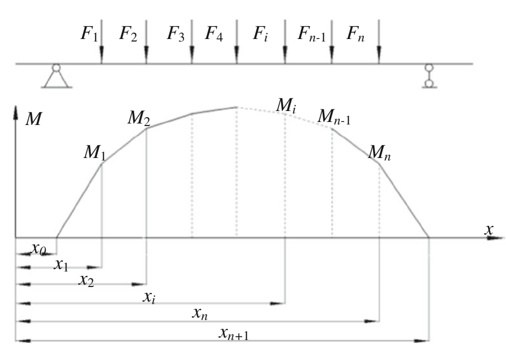

Fig. 9 The moment of multiple concentrated forces applying on the overhanging beam

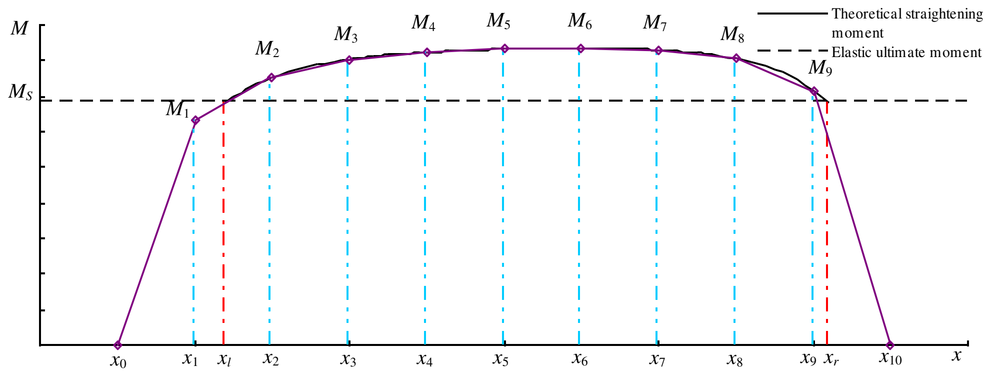

Fig. 10 The sketch of moment when $x_l > x_1$

positions of these pressure points all lie in the region of $[x_l, x_r]$, and the value of M_i is the corresponding theoretical straightening moment at the pressure point x_i; while the number of the pressure points is large, the leftmost pressure point or the rightmost pressure point may lie outside the region of $[x_l, x_r]$—$x_l > x_1$ or $x_n > x_r$. For example, in the situation of $x_l > x_1$ as shown in Fig. 10, M_1 will lie on the intersection point of the extended line through $[x_2, M_2]$ and $[x_l, M_s]$ and the line $x = x_1$, the value of M_1 will be expressed as

$$M_1 = \left(\frac{M_2 - M_s}{x_2 - x_l}\right) \cdot (x_1 - x_l) + M_s \tag{23}$$

Yet, in the situation of $x_n > x_r$, the value of M_n at the pressure point x_n can be expressed as

$$M_n = \left(\frac{M_{n-1} - M_s}{x_{n-1} - x_r}\right) \cdot (x_n - x_l) + M_s \tag{24}$$

Meanwhile, the value of the loading moment at the remaining pressure points still equals to the corresponding theoretical straightening moment;

4. Calculate the straightening force F_i at the pressure point x_i by applying the corresponding position and moment into Eq. 21.

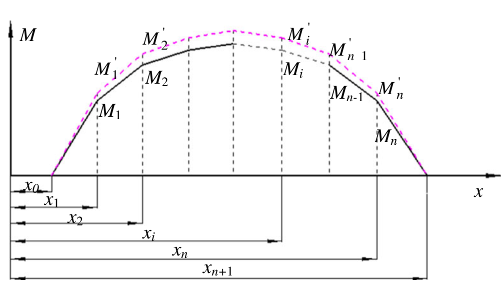

Fig. 11 The sketch of corrected loading moment

5 Load correction coefficient and its optimization method

Given in Fig. 10, only when the number of pressure points tends to be infinite, can the straightening effect of the actually loaded polygonal moment be equivalent to the theoretical straightening moment, and hence, the pipe can be completely straightened. However, only a limited number of pressure points can be used in a practical application, and this would directly result in the actually loaded polygonal moment to be less than the theoretical straightening moment. In order to reduce cost on the required equipment but ensure the straightening precision at the same time, it is more likely to take fewer numbers of the pressure points to make an actually straightening effect similar to the theoretical effect, by modifying the polygonal moment. To reach this goal, a load correction coefficient λ, which is apparently greater than 1, is introduced. The relationship between the corrected moment M_i' and the theoretical moment M_i at the pressure point x_i is

$$M_i' = \lambda M_i \tag{25}$$

As shown in Fig. 11,if distribution of the theoretical straightening moment is $M(x)$, then the distribution of the

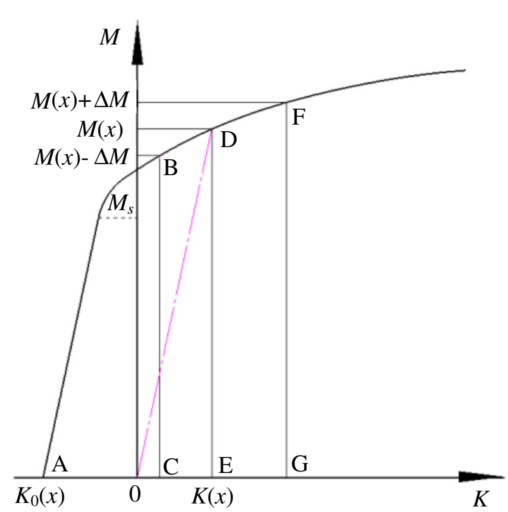

Fig. 12 The relation between moment and curvature

Table 3 FEM results of multi-point straightening process

LJ23-1 pipe	Positions of pressure points and supporting points x/mm								Straightening force F/kN						Residual deflection/mm
	x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	F_1	F_2	F_3	F_4	F_5	F_6	
Five-point bending	700	3400	6100	8800	11500				268.62	27.66	293.53				23.73
Six-point bending	700	2860	5020	7180	9340	11500			303.7	33.65	28.07	341.09			20.46
Seven-point bending	700	2500	4300	6100	7900	9700	11500		322.07	51.99	13.75	39.76	379.37		17.74
Eight-point bending	700	2243	3786	5329	6872	8415	9958	11500	348.02	95.99	15.00	13.33	56.46	404.39	14.68

actually loaded moment after correction will be $M'(x,\lambda)$. The mathematical expression of $M'(x,\lambda)$ is

$$M'(x,\lambda) = \left[\left(\frac{M_{i+1}-M_i}{x_{i+1}-x_i}\right)\cdot x + \left(\frac{M_i x_{i+1}-M_{i+1}x_i}{x_{i+1}-x_i}\right)\right] \qquad x_i < x < x_{i+1} \tag{26}$$

From Eq. 10, the relation between the moment M and the curvature K can be obtained, as shown in Fig. 12. The area under the curve is the bending deformation energy that is produced by loading the moment M on the curved micro-pipe whose initial curvature was K_0. If the initial curvature of the micro-pipe is $K_0(x)$ and its corresponding theoretical straightening moment is $M(x)$, then the area ADE represents the bending deformation energy that is produced by straightening the curved micro-pipe to the straight state. However, if the actually loaded moment is $(M(x)+\Delta M)$, then it will produce the area DEFG larger than the theoretical; if the actually loaded moment is $(M(x)-\Delta M)$, then it will produce the area BCDE smaller than the theoretical. It can be clearly seen from Fig. 12, area DEFG>area BCDE, which indicates that the bending deformation energy is quite different although the absolute values of difference between the actually loaded moment and the theoretical straightening moment are the same in the two cases. This also shows that when the actually loaded moment is greater than the theoretical moment, it will produce a much greater impact on the micro-pipe than one that is less than the theoretical.

Table 4 FEM results with corrected control strategy

LJ23-1 pipe	Optimal load correction coefficient	Residual deflection/mm	Straightness/%
Five-point bending	1.0237	7.48	0.061
Six-point bending	1.0146	5.44	0.045
Seven-point bending	1.0098	6.85	0.056
Eight-point bending	1.0064	7.58	0.062

In accordance with the above discussion, the method is proposed to optimize the value of the load correction coefficient λ, based on the equivalent bending deformation energy. Assume that U_{tr} is defined as the bending deformation energy that is produced by the theoretical moment $M(x)$ loaded on the pipe, and U_{eq} is defined as the bending deformation energy that is produced by the actually loaded moment after correction $M'(x,\lambda)$. Furthermore, U is defined as the absolute difference between U_{tr} and U_{eq}, and the corresponding λ, when U is minimal, is defined as the optimum load correction coefficient. Hence, from Eqs. 10 and 26, U can be expressed as

$$\begin{aligned} U &= \left|U_{tr}-U_{eq}\right| \\ &= \left|\int_{x_e^L}^{x_e^R}\left\{\int_{K_0(x)}^{K(x)} M(K_0(x),K)\mathrm{d}K - \int_{K_0(x)}^{K'(x,\lambda)} M(K_0(x),K)\mathrm{d}K\right\}\mathrm{d}x\right| \\ &= \left|\int_{x_l}^{x_r}\int_{K'(x,\lambda)}^{K(x)} M(K_0(x),K)\mathrm{d}K\mathrm{d}x\right| \end{aligned} \tag{27}$$

where $K'(x,\lambda)$ is curvature of the cross-section center layer when $M'(x,\lambda)$ is loaded on the curved micro-pipe x. The optimum load correction coefficient λ can be obtained by adopting the golden section method to optimize Eq. 27.

6 Verification of the multi-point bending one-off straightening control strategy

As can be seen from Fig. 9, when the multi-point bending pressure straightening process is applied to the actual production, multiple independent pressure points are to be equipped on the straightening equipment, and

Table 5 Geometric and material characteristics of pipe

Material	l/mm	$R_m \times t$/mm	E/GPa	D/MPa	σ_s/MPa
20	1000	72×4	206	2,533	298.7

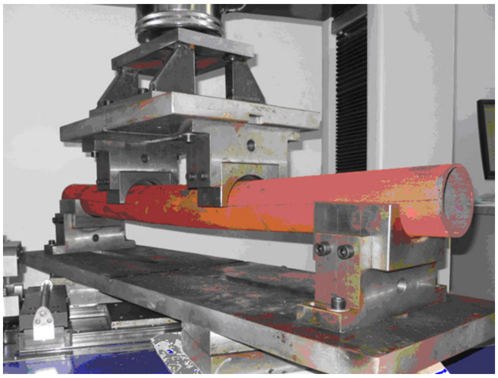

Fig. 13 The four-point bending experimental apparatus

each pressure point needs to have a corresponding system to control the pressure. Nevertheless, the current equipment condition cannot meet these requirements, so that the reliability of the multi-point bending pressure straightening process could only be verified through the FEM simulation.

6.1 FEM simulation results of LSAW pipes

The multi-point bending pressure straightening process for the LSAW pipe is simulated on the basis of the finite element analysis software ABAQUS. Firstly, the finite element model for the LJ23-1 pipe is established. The pipe is 12.213 m-long with the initial deflection measured at 70.89 mm, as shown in Table 1. Some other material property parameters can be acquired from Table 2 and the Poisson ratio ν=0.3. In order to obtain an accurate result, the elementary type is given in 3D solid and incompatible (C3D8I), and the finite element model consists of 22,400 elements. Since this process needs multi-point straightening, if dies are used for loading in the FEM model, the simulation would cost a lot of computing time or likely would not converge. This would result in stop counting, which is caused by possible contact problems in the computational process. Therefore, the coupling constraints are used in this FEM model, that is, a kinematic coupling constrains a surface to the translation and rotation of a master node in a customized manner, then the concentrated force is applied on this master node instead of on the surface. Thus, the force will be increased linearly with time from 0 to a given value.

According to the US API Spec 5L industry standards [10], the maximum allowable deflection for the LJ23-1 pipe cannot be more than 24.43 mm, which is 0.2 % of the pipe length. The test pipe is to be straightened separately with the pressure points of 3, 4, 5, and 6 to calculate the corresponding straightening control parameters from Eqs. 21 to 24. From the calculated parameters and the FEM simulation results shown in Table 3, it can be seen that the final straightness in the all four tests satisfies the standard specified in API Spec 5L. Also, along with the number of increases in pressure points, the actually loaded moment is nearing the theoretical moment with the improved straightening effect. However, in consideration of practical application, the number of pressure points should be as few as possible. According to the straightening parameters shown in Table 3, the optimum load correction coefficient λ can be obtained by adopting the golden section method to optimize Eq. 27. Finally, the corrected forces are applied on the pipe, and the straightening results are shown in Table 4. From Table 4, the following can be noticed: the value of the load correction coefficient λ is gradually decreased as the number of pressure points increased; the deflection of the LSAW pipe can be modified to within 8 mm in one go, by separately using the corrected five-point, six-point, seven-point, and eight-point bending control strategy; the straightness of the LSAW pipe can be straightened within 0.065 %, a significantly improved straightening precision. It becomes clear that the control strategy of the multi-point bending pressure straightening process is suitable for the LSAW pipes. And moreover, a convenient approach is provided for implementing the quantitative control strategy of the multi-point bending process, by using the principle of equivalent bending deformation energy to get the optimum load correction coefficient.

Table 6 Experimental results and FEM results of the four-point experiment

No.	The distance between the pressure points/mm	F_1=F_2/kN	The max deflections when bending/mm		Error/%	The max deflections after springback/mm		Error/%
			Experimental results	FEM results		Experimental results	FEM results	
1	280	20.10	10.44	10.43	0.09	5.04	5.15	2.18
2	280	20.50	13.13	13.59	3.50	8.30	8.21	1.08
3	280	20.75	15.69	16.08	2.5	10.65	10.64	0.09
4	320	21.35	10.22	10.27	0.48	5.02	4.90	2.39
5	320	21.70	12.43	12.75	2.57	7.22	7.29	0.09
6	320	22.05	15.90	16.05	0.94	10.29	10.49	1.9

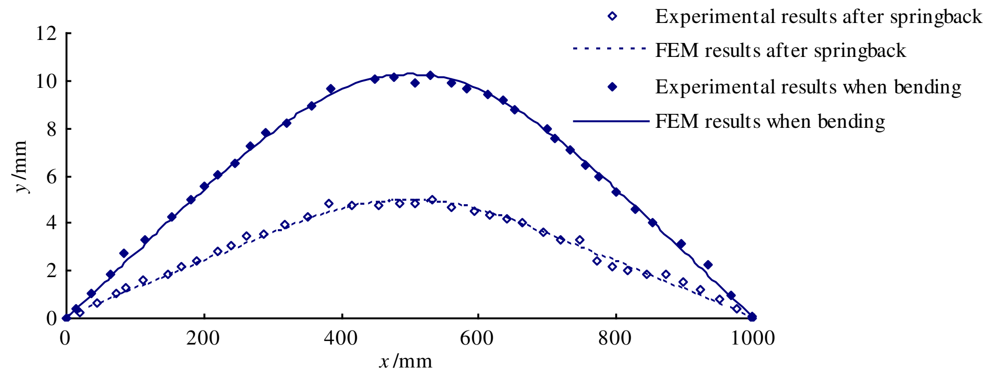

Fig. 14 The deflection distributions of the No.4 pipe when bending and after springback

6.2 Experimental verification of the FEM model

The reliability of this FEM simulation model is verified through physical simulation experiments, in which the four-point bending process is applied on the small-sized straight pipes. The geometric and material characteristics of the pipes are shown in Table 5. The bending experiments are carried out with the WDD-LCT-150 material testing machine, and the four-point bending experimental apparatus is shown in Fig. 13. The distance between the pressure points and the distance between the supporting points are both adjustable when needed. In the experiments, the distance between the supporting points is fixed as 900 mm. Due to structural limitations of the experimental apparatus, each bending in the experiments is a symmetric four-point bending, and the concentrated forces applied at the two pressure points are the same, i.e., $F_1=F_2$. Deflection distributions of the pipes when bending and after springback are measured using the 3000iTM portable coordinate measuring instrument, which is manufactured by CimCore and has a measurement accuracy of 0.01 mm. Parameters and results of the four-point bending experiments are shown in Table 6, and deflection distributions of the No. 4 pipe when bending and after springback are shown in Fig. 14. Table 6 shows that the maximum error between the experimental results and FEM results is 3.5 % when bending and 2.39 % after springback. These errors are smaller than 5 %, thus the reliability of this FEM simulation model with coupling constraints is verified by physical simulation experiments.

7 Conclusions

1. Based on the springback equation of the small curvature plane bending, the principle and expression for determining the theoretical straightening moment corresponding with the initial deflection distribution of a LSAW pipe is proposed. Theoretically, the LSAW pipe could be completely straightened in one go when such straightening moment is imposed. As a theoretical basis, quantification of the theoretical straightening moment distribution makes it possible to study various pressure straightening control strategies.
2. The control strategy of the multi-point bending one-off straightening process for LSAW pipes is introduced and studied, by discretizing and linearizing the theoretical moment curve. Also, the method to determine the corresponding straightening parameters is established.
3. The feasibility of the multi-point bending one-off straightening control strategy is verified by the FEM simulation results of a LSAW pipe, while the reliability of the FEM simulation model is validated by the physical simulation experiments of small-sized pipes.
4. In order to reduce cost on the required equipment while also ensuring the straightening precision, it is more likely that a fewer number of pressure points can be used to achieve a straightening effect that is similar to the theoretical straightening effect. For this purpose, a load correction coefficient λ is introduced, and the optimum load correction coefficient can be determined on the basis of the principle of equivalent bending deformation energy, according to the multi-point bending one-off straightening control strategy. The FEM simulation results show that the deflection of a LSAW pipe can be modified from its initial 70.89 mm into less than 8 mm in one go by using the corrected control strategy, when numbers of pressure points are set up as 3, 4, 5, and 6, so that the straightness of the pipe is improved within 0.065 %, which is far less than the standard requirement of 0.2 %.
5. For a future multi-point bending automatic straightening machine, the two main characteristics required by the multi-point bending one-off straightening control strategy are being equipped with an online system to detect a pipe's deflection distribution and being equipped with an independent pressure control system on each pressure point.

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