Two-Roller Continuous Calibration Process by Compression for Submarine Pipelines

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Abstract: Submarine pipeline is a key part in the development of deep sea and ultra-deep sea oil and gas. In order to reduce the ovality of pipes and improve their compressive strength, a two-roller continuous calibration (TRCC) process by compression is proposed. A springback analysis of compress bending is carried out, and an analytical model is established, which predicts ovality after calibration and provides a theoretical basis for roller shape design and process parameter formulation. Numerical simulation and physical experiments are carried out. The distribution of stress and strain is analyzed. The effects of initial ovality, reduction ratio and initial placement angle on the ovality after calibration are studied. When the reduction ratio is about 1%, the ovality is optimal. The theoretical analysis shows that the ovality after calibration is about 0.03%, and the ovality after calibration by numerical simulation and experiment is less than 0.45%, proving the feasibility of the process.

Keywords: submarine pipelines; two-roller continuous calibration process; compress bending; springback; ovality

1. Introduction

Marine oil and gas have become the main source of world oil production growth. As the oil and gas transportation carrier, submarine pipeline is the basic guarantee for the development of marine oil and gas resources. With the development of marine resources exploitation from offshore to deep sea, due to the harsh special environment of the deep sea, including the tide, geological changes, deep-sea high pressure, seawater corrosion, and other factors, the requirements of pipe strength, toughness, plasticity, compressive collapse performance, dimensional accuracy, and other aspects are more stringent, forcing a change in the submarine pipeline manufacturing process.

The current main manufacturing processes of submarine pipeline include UOE [1–3] and JCO [4,5]. In order to meet the ovality standard [6], a calibration process is needed after forming, mostly an expanding process. However, under the high pressure generated by material deposition and seawater pressure, submarine pipelines often suffer structural instability, and the ability to resist this instability depends on the defects and residual stresses generated in the pipeline manufacturing process [7]. The expanding process originally used in onshore pipeline manufacturing may be suitable for deep sea [8]. Yu et al. [9] analyzed the influence of crack parameters on the fatigue life of deep-water submarine pipelines and found that pipeline cracks are the main cause of failure accidents. Feng et al. [10] theoretically analyzed the anti-collapse performance of submarine pipelines, and the results showed that ovality is an important factor affecting the anti-collapse performance of pipelines. Madhav et al. [11] analyzed the influence of the Bauschinger effect on the UOE
forming process and found that the expanding process enlarges small cracks, holes, and other defects. Due to the Bauschinger effect, expanding tends to increase the yield stress in the circumferential tensile direction and decrease the yield stress in the compressive direction [12]. A large number of studies shows that the expanding process will greatly reduce the collapse resistance of the pipeline [7,13,14]. Therefore, Kyriakides et al. [15] proposed that a compression process should be used instead of an expanding process to avoid the reduction of pipeline compressive strength. If a pipeline is compressed to a high enough strain (1.0%), its collapse resistance can be improved. Therefore, a calibration process of compression instead of expansion would be a better choice.

Some theoretical and experimental studies on the calibration process by compression have been concluded. Pan et al. [16] proposed a rounding and sizing process, which produced a permanent deformation of about 0.5% of the circumference by the two-half mold to achieve rounding and sizing. Yin et al. [17] proposed a compression and setting round process by using upper and lower dies with the closed cavity as a full circle, and then completed a springback analysis. Zhao et al. [18] combined JCO forming with a calibration process by compression and verified that this calibration process had the same sizing effect as an expansion process. Zhao et al. [19] proposed an over-bending setting round process for the end of large pipes by a mold press and developed its control strategy. Yuan et al. [20] analyzed the influence of different friction coefficients and feed rates on the forming effect in the compression and setting round process by numerical simulation. Yu et al. [21] studied the three-roller setting round process and their results showed that when the elastic area ratio is close to 40%, the residual ovality is close to 0.3%, which effectively reduces the ovality. However, most of the above processes belong to progressive finishing, which are more suitable for pipe-end setting round, and the work efficiency is low. Huang et al. [22] proposed a three-roller continuous setting round process, which improves the production efficiency, and the ovality of pipes after setting round was about 0.2%. Kim et al. [23] established an analytical model to predict the final radius of three-roller setting round. Zhang et al. [24] analyzed the failure mode of thick-walled submarine pipeline and proposed the interaction mechanism of ovality and eccentricity on the failure response. Yu et al. [1] established a three-dimensional model of UOE forming process and analyzed its crush resistance. The results showed that a greater compressive or expansive force is needed to reduce the ovality of the pipeline.

In this paper, a two-roller continuous-calibration (TRCC) process by compression is proposed to calibrate submarine pipelines. A springback analysis of compress bending is carried out, and an analytical model is established, which predicts ovality after calibration and provides a theoretical basis for both roller shape design and process parameter formulation. A numerical simulation and physical experiments are carried out to verify the feasibility of this process. The distribution of stress and strain is analyzed. The effects of initial ovality, reduction ratio and initial placement angle on the ovality after calibration are studied.

2. TRCC Process

The TRCC machine is mainly composed of two working parts, an upper roller and lower roller, as shown in Figure 1. The two rollers are closed to form a circular cavity and are symmetrical. The two rollers rotate in opposite directions, and the pipe is fed in via the action of friction. The pipe is reduced in diameter and the purpose of the calibration is completed. By designing the size of the circular cavity, the calibration with different reduction rates can be realized. In the process, continuous local loading not only reduces the tonnage, but also improves the efficiency of the calibration process.
The TRCC process can be divided into three stages: rounding, compression, and springback, as shown in Figure 2. Only elastic deformation occurs when the pipe is in position B. From position B to position C, the deformation of the pipe changes from elastic to plastic, and the plastic deformation region expands along the thickness and circumferential directions as the pipe is fed. When the pipe is in position D, it is unloaded and rebounded to complete the continuous calibration of the whole pipe.

3. Mechanical Analyses

The diameter: thickness ratio of large submarine pipelines is large. In the calibration process, the curvature of the pipe changes little, and belongs to the small deformation problem, so the pipe is subjected to the combined action of compression and bending. Based on the springback theory of small curvature plane bending [25], a springback analysis of compress bending was carried out.

3.1. Compress Bending Springback Analysis

The shape of the geometric center layer of pipe was assumed to be ovality. One of the pipe’s microbeams was taken as the analysis object, as shown in Figure 3. \( \rho_0 \) is the initial curvature radius of the section’s geometric center layer, the section of pipe wall is rectangular, the section height is the pipe thickness \( t \), and \( B \) is the section width.
The bilinear hardening model is used, the relationship between stress $\sigma$ and strain $\epsilon$ is as follows:

$$\sigma = \begin{cases} E\epsilon & 0 < \epsilon < \frac{\sigma_0}{E} \\ D\epsilon + \frac{\sigma_0}{E} & \frac{\sigma_0}{E} < \epsilon \end{cases}$$  \hspace{1cm} (1)$$

where $\sigma_0$ is yield stress, $E$ is elastic modulus, and $D$ is plastic modulus.

Considering the shape of the initial pipe microbeam, the initial equivalent strain $\epsilon_0$ is introduced, and it can be expressed as

$$\epsilon_0 = \frac{y}{\rho_0}, \quad -\frac{t}{2} \leq y \leq \frac{t}{2}$$  \hspace{1cm} (3)$$

The equivalent strain of pipe microbeam is introduced, and its value is the algebraic sum of initial equivalent strain $\epsilon_0$ and true strain $\epsilon_{tr}$ as follows:

$$\epsilon_{ep} = \epsilon_0 + \epsilon_{tr}$$  \hspace{1cm} (4)$$

3.1.1. Loading Strain

The equivalent strain is shown in Figure 4 when the pipe microbeam loading is under the combined action of tangential force $T$ and bending moment $M$. As shown in Figure 4, the curvature radius of the equivalent strain neutral layer is changed to $\rho_\epsilon$ and the curvature radius of the geometric center layer of the microbeam is changed to $\rho$. The coordinate system $x_1\rho_1y_1$ is established, and the $x$ axis coincides with the neutral layer of equivalent strain.

Equation (4) can be expressed by

$$\frac{y_1}{\rho_\epsilon} = \epsilon + \epsilon_0, \quad \rho - \rho_\epsilon - \frac{t}{2} \leq y_1 \leq \rho - \rho_\epsilon + \frac{t}{2}$$  \hspace{1cm} (5)$$

Transform coordinate $y_1$ into $y$,

$$y_1 = y + \rho - \rho_\epsilon$$  \hspace{1cm} (6)$$
Then
\[ \varepsilon = \frac{y + \rho - \rho_e}{\rho_e} - \frac{y}{\rho_0} = y\left(\frac{1}{\rho_e} - \frac{1}{\rho_0}\right) + \frac{\rho - \rho_e}{\rho_e}, -\frac{t}{2} \leq y \leq \frac{t}{2} \]  

(7)

3.1.2. Strain after Unloading

The strain after unloading \( \varepsilon_p \) is still a linear distribution in the cross-section of pipe, as shown in Figure 5. The curvature radius of the residual equivalent strain neutral layer is \( \rho_{ep} \), and the curvature radius of the geometric center layer is \( \rho_p \). The coordinate system \( x_2o_2y_2 \) is established, and the \( x_2 \) axis coincides with the neutral layer of equivalent strain after unloading.

![Figure 5. Equivalent strain after unloading.](image)

Equation (4) can be expressed by

\[ \frac{y_2}{\rho_{ep}} = \varepsilon_p + \varepsilon_0, \rho - \rho_e - \frac{t}{2} \leq y_2 \leq \rho - \rho_e + \frac{t}{2} \]  

(8)

Transform coordinate \( y_2 \) into \( y \),

\[ y_2 = y + \rho_p - \rho_{ep} \]  

(9)

Then

\[ \varepsilon_p = \frac{y + \rho_p - \rho_{ep}}{\rho_{ep}} - \frac{y}{\rho_0} = y\left(\frac{1}{\rho_{ep}} - \frac{1}{\rho_0}\right) + \frac{\rho_p - \rho_{ep}}{\rho_{ep}}, -\frac{t}{2} \leq y \leq \frac{t}{2} \]  

(10)

3.1.3. Elastic Strain under Reverse Loading

According to the unloading law, the springback strain \( \varepsilon_t \) is produced by the tangential force \( T_e \) and bending moment \( M_e \), which are equal, opposite, and at the same action points of the tangential force \( T \) and bending moment \( M \), as shown in Figure 6. The curvature radius of the elastic equivalent strain neutral layer is \( \rho_{ee} \), and the curvature radius of the geometric center layer is \( \rho_e \). The coordinate system \( x_3o_3y_3 \) is established, and the \( x_3 \) axis coincides with the neutral layer of elastic equivalent strain.

![Figure 6. Elastic equivalent strain under reverse unloading.](image)
Equation (4) can be expressed by
\[
\frac{y_3}{\rho_{ee}} = \varepsilon_e + \varepsilon_0, \quad \rho_e - \rho_e \leq \frac{t}{2} \leq y_3 \leq \rho_e - \rho_e + \frac{t}{2}
\] (11)

Transform coordinate \(y_3\) into \(y\),
\[
y_3 = y + \rho_e - \rho_{ee}
\] (12)

Then
\[
\varepsilon_e = \frac{y + \rho_e - \rho_{ee} - y}{\rho_0} = y\left(\frac{1}{\rho_{ee}} - \frac{1}{\rho_0}\right) + \frac{\rho_e - \rho_{ee}}{\rho_{ee}}, -\frac{t}{2} \leq y \leq \frac{t}{2}
\] (13)

### 3.1.4. Springback Equation

The relationship of \(\varepsilon_p, \varepsilon_e, \) and \(\varepsilon\) is given by
\[
\varepsilon_p = \varepsilon_e + \varepsilon
\] (14)

By Equations (7), (10) and (13), Equation (14) can be expressed by
\[
y\left(\frac{1}{\rho_{ep}} - \frac{1}{\rho_e} - \frac{1}{\rho_{ee}} + \frac{1}{\rho_0}\right) = \frac{\rho}{\rho_e} + \frac{\rho_e - \rho_{ep}}{\rho_{ee}}, -\frac{t}{2} \leq y \leq \frac{t}{2}
\] (15)

The necessary and sufficient conditions for Equation (15) to be permanent is that the left and right sides are zero. That is
\[
\begin{cases} 
\frac{1}{\rho_{ep}} - \frac{1}{\rho_e} - \frac{1}{\rho_{ee}} + \frac{1}{\rho_0} = 0 \\
\frac{\rho}{\rho_e} + \frac{\rho_e - \rho_{ep}}{\rho_{ee}} = 1 
\end{cases}
\] (16)

Elastic strain \(\varepsilon_e\) corresponds to stress \(\sigma_e\), then
\[
\sigma_e = E\varepsilon_e = yE\left(\frac{1}{\rho_e} - \frac{1}{\rho_0}\right) + E\left(\frac{\rho_e - \rho_{ep}}{\rho_{ee}}\right), -\frac{t}{2} \leq y \leq \frac{t}{2}
\] (17)

It can be known from the definition of force and bending moment that
\[
T_e = \int_A \sigma_e dA = E \cdot A \left(\frac{\rho_e}{\rho_{ee}} - 1\right)
\] (18)
\[
M_e = \int_A \sigma_e \cdot y dA = EI_z \left(\frac{1}{\rho_{ee}} - \frac{1}{\rho_0}\right)
\] (19)

According to the equilibrium condition of force, it can be known that
\[
\begin{cases} 
T + T_e = 0 \\
M + M_e = 0 
\end{cases}
\] (20)

By Equations (16) and (18)–(20), \(\rho_p\) is given by
\[
\rho_p = \frac{I_z (\rho EA - T \rho_e)}{A (EI_z - M \rho_e)}
\] (21)

### 3.2. Ovality after Two-Roller Calibration Process

The circumferential strain of the central layer of the pipe section can be obtained by Equations (7) and (13), as follows
\[
\varepsilon|_{y=0} = \frac{\rho - \rho_e}{\rho_e} = \frac{R_1 - \rho_e}{\rho_e}
\] (22)
where $R_1$ is the radius of the central layer of the pipe section.

The circumferential strain of the center layer of the section expressed by Equation (22) can also be expressed as

$$
\varepsilon_{\mid y=0} = \frac{L_1 - L_0}{L_0} = \frac{R_1 - R_0}{R_0} = -\delta
$$

where $\delta$ is the reduction rate, $L_0$ is the initial circumference, and $L_1$ is the circumference after calibration process.

According to Equations (22) and (23),

$$
\rho_{\varepsilon} = R_0
$$

In the calibration process, all the particles of the pipe are subjected to compressive strain and plastic deformation.

By Equations (1), (7) and (24),

$$
\sigma = D\left[y\left(\frac{1}{R_0} - \frac{1}{\rho_0}\right) - \delta\right] - \sigma_0
$$

The tangential force $T$ and bending moment $M$ can be known by

$$
\begin{align*}
T &= B\int_{\frac{3}{4}}^{\frac{5}{4}} \sigma dz = A(D\delta - \sigma_0) \\
M &= B\int_{\frac{3}{4}}^{\frac{5}{4}} \sigma z dz = D\delta\left(\frac{1}{R_0} - \frac{1}{\rho_0}\right)
\end{align*}
$$

By Equations (21), (24) and (26), the springback equation can be expressed as

$$
\rho_p = \frac{\sigma_0}{\sigma} + 1 + \delta\left(D\delta - \frac{1}{\rho_0}\right)R_0
$$

The ovality after unloading can be expressed as

$$
\varphi = \frac{2(a - b)}{a + b}
$$

$$
\begin{align*}
a &= \sqrt{\rho_{pa} \cdot \rho_{pb}^2} \\
b &= \sqrt{\rho_{pb} \cdot \rho_{pa}^2}
\end{align*}
$$

where $\varphi$ is the ovality after unloading, $\rho_{pa} = \rho_p\mid_{\rho_0 = \rho_{pa}}$, $\rho_{pb} = \rho_p\mid_{\rho_0 = \rho_{pb}}$.

4. Finite Element Model

The TRCC process was simulated by ABAQUS 6.14 (Dassault Systèmes Corp. Waltham, MA, USA), the finite element model is shown in Figure 7. The pipe material was 20 steel, and its performance parameters are shown in Table 1. The dimensions of the rollers are shown in Figure 8. Different reduction ratios can be achieved by adjusting $R$. 
The ovality after unloading can be expressed as:
\\[
\phi = \sqrt{\frac{a^2 - b^2}{a^2 + b^2}}
\]

where \(a\) and \(b\) are the major and minor axes of the ellipse, respectively.

Table 1. Performance parameters of pipe.

| Yield Stress \(\sigma_s/\text{MPa}\) | Elastic Modulus \(E, \text{GPa}\) | Plastic Modulus \(D, \text{MPa}\) | Tensile Strength \(\sigma_b, \text{MPa}\) | Poisson Ratio \(\nu\) | Density, \(\rho/(\text{kg}\cdot\text{m}^{-3})\) |
|-----------------------------------|---------------------------------|---------------------------------|-------------------------------|-----------------|-----------------|
| 298                              | 206                             | 2533                            | 701                           | 0.3             | 7.85 \times 10^{-9} |

Figure 7. Finite element model of the TRCC process.

Figure 8. Dimensions of the roller in the TRCC process.

The pipe was set as a deformable body, the linear simple integration units were used, the size of each unit was 1 mm in the circumferential direction, and the pipe wall was divided into four layers in the thickness direction to achieve high simulation accuracy. The roller dies were set as a rigid body, and the surface–surface hard contact type was adopted, the size of each unit was 1 mm in the circumferential direction, and the pipe wall was divided into four layers in the thickness direction to achieve high simulation accuracy. The roller dies were set as a rigid body, and the surface–surface hard contact type was adopted, the penalty function was used for the tangential behavior, and the friction coefficient was 0.18. Since the TRCC process is a nonlinear dynamic process, ABAQUS/Static Implicit solver was adopted.

5. Experimental Device

A scaled-down TRCC device (Yanshan University, Qinhuangdao, China) was developed to be used to verify the feasibility of the process, as shown in Figure 9. The device is mainly composed of upper lower rollers, frame, a transmission system, and a power system. In the calibration process, the profile of the upper and lower roller forms a circle. There is a 2 mm gap between the two rollers. The pipe selected for the experiment is the same as that for the simulation. In order to reduce the experimental cost compared to the submarine pipe, the size of the experimental pipe was scaled equally. In the calibration process for pipes, the scale effect can be ignored [22,26–29].
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5. Experimental Device

Figure 9. Experimental device of the TRCC process.

6. Results and Discussion

6.1. Stress and Strain

The initial ovality of the pipe was 2.5%, the reduction rate was 0.5% and the roller gap was 2 mm. Based on the above conditions, the deformation of the pipe was studied. In the calibration process, the major axis of ovality was along the vertical direction. The upper and lower regions of the pipe were compressed and bent reversely, and the left and right regions were compressed and bent positively.

The distribution of equivalent stress is shown in Figure 10. It can be seen that the equivalent stress distribution on the section is uniform in the local loading position. The value is greater than yield stress, which indicates that all areas of the pipe undergo plastic deformation during the calibration process.

![Equivalent stress distribution after the TRCC process.](image)

Figure 10. Equivalent stress distribution after the TRCC process.

The distribution of the three principal stresses is shown in Figure 11. It can be seen that the tangential stress is the largest of the three principal stresses. This shows that compression plays a leading role, not bending. However, due to the initial ovality, the distribution of the three principal stresses at different positions is uneven, especially in the left and right sections, and the upper and lower sections.
compression plays a leading role, not bending. However, due to the initial ovality, the distribution of the three principal stresses at different positions is uneven, especially in the left and right sections, and the upper and lower sections.

Figure 11. Distribution of the three principal stresses after the TRCC process: (a) radial stress, (b) tangential stress, and (c) axial stress.

The distribution of equivalent strain is shown in Figure 12. It can be seen that because of the combined action of compression and bending, and the initial ovality, the distribution of equivalent strain is not uniform. The equivalent strain gradually decreases from the reverse bending region to the positive bending region. The equivalent strain increases gradually from the outer surface to the inner surface in the positive bending region. In the reverse bending region, the equivalent strain gradually decreases from the outer surface to the inner surface.

Figure 12. Equivalent strain distribution after the TRCC process.

The distribution of the three principal strains is shown in Figure 13. It can be seen that different degrees of deformation occurred in the three directions. Because of the combined action of compression and bending, the initial ovality, the distribution of the three...
The distribution of the three principal strains is shown in Figure 13. It can be seen that different degrees of deformation occurred in the three directions. Because of the combined action of compression and bending, and the initial ovality, the distribution of the three principal strains is unevenly distributed. The tangential strain is the maximum principal strain.

Figure 13. Distribution of three principal strains after TRCC process: (a) radial strain, (b) tangential strain, and (c) axial strain.

6.2. Evaluation of Ovality

In order to study the variation of ovality after calibration with initial ovality and reduction rate, the pipe with thickness of 3 mm and outer diameter of 45 mm was selected. The initial ovality included 1.5%, 2.5%, 3.5%, and 4.5%. The reduction rate included 0.5%, 1.0%, 1.5%, and 2.0%. The experimental and theoretical results are shown in Figure 14. When the initial ovality was 1.5%, theoretical calculation, numerical simulation, and experiments were carried out; the results are shown in Figure 15.

As shown in Figure 14, the ovality after calibration decreases with the increase in the reduction rate, and finally tends to be saturated. Figure 15 shows that the ovality after calibration decreases first and then increases with the increase in the reduction rate, and finally tends to be saturated, which indicates that the calibration effect is optimal when the reduction rate is about 1% from the results of theoretical calculation and numerical simulation. The ovality obtained by theoretical calculation is much better than that by numerical calculation and experiments.

When the reduction rate was 1%, theoretical calculation, numerical simulation, and experiments were carried out to study the influence of initial ovality and initial placement angle on the ovality after calibration, and the results are shown in Figures 16 and 17.
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tment angle on the ovality after calibration, and the results are shown in Figures 16 and

Figure 14. The variation in ovality after calibration with initial ovality and reduction rate.

Figure 15. The influence of reduction rate on the ovality after calibration when the initial ovality

is 1.5%.

Figure 16. The influence of initial ovality on the ovality after calibration.
Figure 17. The influence of initial placement angle on the ovality after calibration.

Figure 16 shows that the ovality after calibration increases with the initial ovality. The ovality after calibration is negatively correlated with the initial ovality. Figure 17 shows that the ovality after calibration is not changed with the initial placement angle. This indicates that the ovality after calibration is independent of the initial placement angle.

7. Conclusions
(1) A TRCC process by compression was proposed for submarine pipelines to reduce the ovality and residual stress, and to increase the compressive yield strength in order to improve the collapse pressure of the pipe in deep sea. In the process, the continuous local loading not only reduces the tonnage of the equipment, but also improves the efficiency of the calibration process. The ovality after calibration was about 0.03% by theoretical calculation, and the ovality after calibration was less than 0.45% by numerical simulation and experiment, which proves the feasibility of the process.
(2) The springback analytical model of TRCC process was established, and the ovality after calibration was predicted, which provides a theoretical basis for roller shape design and process parameters formulation.
(3) The process is part of local continuous loading. Under the combined action of compression and bending, the deformation is complex, and the pipe is in a state of triaxial stress and triaxial strain.
(4) The ovality after calibration decreases with the increase in reduction ratio, and finally tends to be saturated. It is only somewhat related to the initial ovality but is unrelated to the placement angle of the pipe. When the reduction ratio is about 1%, the ovality after calibration is optimal.

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