UOE PIPE MANUFACTURING PROCESS SIMULATION: 
EQUIPMENT DESIGNING AND CONSTRUCTION

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Abstract: UOE pipe manufacturing process influence directly on pipeline resilience and operation capacity. At present most spreaded pipe manufacturing method is UOE. This method is based on cold forming. After each technological step appears a certain stress and strain level. For pipe stress strain study is designed and constructed special equipment that simulate entire technological process. UOE pipe equipment is dedicated for manufacturing of longitudinally submerged arc welded DN 400 (16 inch) steel pipe.

Key words: UOE pipe, die, punch, springback, strain

1. Introduction

UOE pipe manufacturing process is based on cold forming process. Cold forming is process by which metal is shaped without removing material.

International abbreviation UOE represents principal mechanical steps, so U – represents when plate is formed into U - shape, O– represents the moment when U shape is pressed into circular shape and final step E– represent expanding operation that means obtaining standard size of pipe, but always, first step is edge crimping operation that means edge preparing for weld seam execution, i.e. edges crimping into circular shape [1].

Bending process, involves cold forming. Obtaining of desire shape depends on spring back phenomenon. Spring back is the geometric change made to a part at the end of the forming process when the part has been released from the forces of the forming tool [2]. Bending radius calculation considering spring back is the first step regarding equipment designing. After, the strip is bent, through a less radius than required and the work piece springs back to the required radius. Purpose of this paper is equipment designing and construction for manufacturing of longitudinally submerged arc welded DN 400 steel pipe. Due to pipe long length, equipment is designed for pipe length of 30 mm.

2. Punch bending radius calculation

Usually, spring back phenomenon is expressed in angular units of measurement and represents the value with which the bending angle should be decreased to obtain the required angle to the bent strip [3].
Based on figure 1, is considered that fictive bending moment is applied on bended strip and is acting in the opposite direction to the one that produced the bending (actually is the moment produced by the tensions that cause the elastic deformation). In same time, fictive moment modifies neutral axis radius of curvature $r_f > r$. At the end of the bending operation, the radius of curvature of the neutral axes is $r$. From this overlapping will result residual strain that corresponding to the radius of curvature $r_r > r$. The same issues are valid to the angle between two sections normal to neutral axis ($AA → A'A'$, $BB → B'B'$), namely $\alpha_r > \alpha_0$ [4].

Between the three radiiuses of curvature exists the next relation:

$$\frac{1}{r_r} = \frac{1}{r} - \frac{1}{r_f} \quad (1)$$

Considering that radius of curvature is imposed by punch radius, so:

$$r = r_p + \frac{s}{2} \quad (2)$$

The fictive radius of curvature $r_f$ is determined by fictive bending moment which produces just elastic strain, namely:

$$\frac{1}{r_f} = \frac{M_{xf}}{E I_y} \quad (3)$$

where $M_{xf}$ is the fictive bending moment, considered equal with the moment of deformation forces ($M_{xf} = M$), and $I_y$ – section moment of inertia, in this case $I_y = \frac{bh^3}{12}$.

Replacing (3) in (1) is obtained:

$$\frac{1}{r_r} = \frac{1}{r} - \frac{M_x}{E I_y} \quad (4)$$

From which is results:

$$r_r = \frac{r}{1 - \frac{M_x r}{E I_y}} \quad (5)$$

The condition that the length of the neutral axis to be the same before and after bending can be expressed in the next form:

$$r \alpha_0 = r_r \alpha_r \quad (6)$$

and angle of elastic return (spring back) is:

$$\Delta \alpha = \alpha_0 - \alpha_r \quad (7)$$

With relations (5) and (7), this return angle becomes:
\[ \Delta \alpha = \alpha_0 \left(1 - \frac{r}{r_f}\right) = \alpha_0 \frac{M_x r}{E I_y} \]  

Taking into account the bending moment expression, relation (8) takes the next form:

\[ \Delta \alpha = 3\alpha_0 \frac{r \sigma_Y}{h E} \]  

(9)

On the other hand, the relation (5) can also be written as:

\[ r_r = \frac{r}{1 - 3\alpha_0 \frac{r \sigma_Y}{h E}} \]  

(10)

From this relation is determined punch radius \( r_p = r \). This radius permits to obtain, after bending, certain radius - \( r \):

\[ r_p = \frac{r}{1 + 3\alpha_0 \frac{r \sigma_Y}{h E}} \]  

(11)

After inserting the data necessary to determine the punch radius the following value is obtained:

\[ r_p = \frac{199}{2 + 1.18 \times 10^5} = 171 \text{mm} \]  

(12)

where:

- \( r_p \) - punch radius, mm;
- \( h \) - plate thickness, mm;
- \( r \) - the desired radius, mm;
- \( \sigma_Y \) - Yield point, MPa;
- \( E \) - elastic limit, MPa;

Punch radius determination is essential for entire pipe manufacturing process. In order to be sure of the correct calculation of the punch radius, based on Rudman deduced formula, a calculation is performed. It should be noted that, these formulas are valid for the practical calculations.

First of all, is calculated coefficient - \( K_p \), which characterizes the material and is determined, experimentally [5]:

\[ K_p = 0.375 \cdot \frac{\sigma_Y}{E} \cdot 10^4 = 8.22 \]  

(13)

The punch radius calculation is performed by the next formula [5]:

\[ r_p = \frac{h}{r + 8K_p \cdot 10^{-4}} = 171 \text{ mm} \]  

(14)

where:

- \( r_p \) - punch radius, mm;
- \( h \) - plate thickness, mm;
- \( r \) - the desired radius, mm;
- \( K_p \) coefficient, which characterizes the material proprieties;

### 3. Punch for edge crimping

Pipe manufacturing process is starting with plate edge crimping operation. To obtain required punch is necessary to be followed next steps [6]:

- Drawing up the technical drawing;
- Choosing the material;
- Cutting;
- Cleaning;
- Assembly;
- Quality control;
It should be noted that, all equipments which are involved in manufacturing process, are inspired by reality. Example for edge crimping punch is edge crimping press from Siempelkamp company, presented in figure 2 [7].

Figure 2: Edge crimping press from Siempelkamp company, by (7)

Based on edge crimping press [7] and calculated punch radius, technical drawing is performed by specialized software AutoCAD 2013 (student version) [8]. Here after, in figure 3 is presented edge crimping punch drawing.

The material required to execute the punch is taken from high strength low alloy steel A36 (the die and the punch are generally made of a material with a higher hardness than strip to be processed) with plate thickness $h = 30$ mm [9].

Material cutting is an important step, because radius correct execution influences entire pipe manufacturing process. From this reason, material is cut using abrasive water jet cutting machine, MAXIEM 1530 [10].

Figure 3: Edge crimping punch (technical drawing)

1- Punch, 2- Die

After going through all steps, is obtained edge crimping punch presented in figure 4.

Figure 4: Edge crimping punch (in reality)
4. „U” – shape bending equipment

Next step in manufacturing process, represents U shape forming. Same as for edge crimping punch, U – shape bending equipment is is inspired by reality. In figure 5 is presented U –ing press from EuroPipe company, Mülheim an der Ruhr, Germany [11].

For U – shape bending equipment obtaining it is necessary to be followed the same process:
• Drawing up the technical drawing;
• Choosing the material;
• Cutting;
• Cleaning;
• Assembly;
• Quality control;

Technical drawing is performed by specialized software AutoCAD 2013 (student version) [8].

Due to the impossibility of getting of plate with thickness \( h = 30 \) mm, the material required to execute the U - shape bending machine, is taken from high strength low alloy steel A36 with plate thickness \( h = 20 \) mm [9]. Taking into account, the close link between design, materials and intended purpose, has emerged the need to adapt the equipment. From this reason, it was necessary to add an insertion. Must be mentioned that insertion radius is equal with 179 mm (also taking into account the thickness of the plate).

Here after, design result is presented in figure 6.

![Image of U-press](image)

Figure 5: U–ing press from EuroPipe company, by (11)

Material is cut using abrasive water jet cutting machine MAXIEM 1530 [10].
After designing, material choosing, cutting follows the equipment assembling using welding. Obtained result is presented in figure 7.

![Figure 6: U-shape bending machine (technical drawing)](image1)


5. "O" – shape bending equipment

This step represents the moment when the plate (strip) is pressed into circular shape. The equipment for O shape bending actually represents a combination of two semicircles. Designing of this equipment is based on O-ing press EuroPipe company, Mülheim an der Ruhr, Germany [11].

![Figure 8: O-ing press from EuroPipe company, by (11)](image2)

Technical drawing is performed by specialized software AutoCAD 2013 (student version) [8]. Equipment design is based on O-ing press, as shown in figure 9. Taking into account, the major changes in the shape of the plate, for safety and controlling of the technological process, these two semi circles are provided with the guidings 3 and 4. Here after, O shape bending result is presented in figure 10.
Certain materials come from previous step, namely die is the same with U-ing press, but without insertion. The materials for punch is taken from high strength low alloy steel A36 with plate thickness $h = 20$ mm [9].

Materials are cut using abrasive water jet cutting machine MAXIEM 1530 [10]. After designing (figure 9), material choosing, cutting follows the equipment assembling using welding. Obtained result is presented in figure 10.

6. Mechanical expander

In reality, pipe is loaded by using mechanical expander, but for simulation will be used especially manufactured expander for DN 400 pipe expanding. Expanding operation is the last step in principal manufacturing process, from this reason equipment must to meet all the conditions to achieve the same results as those in reality. Mechanical expander designing is based on mechanical expander from Corus Tubes, Tata steel company, United Kingdom [12], but taking into account simulation conditions, equipment is adapted to hydraulically press.

![Figure 9: „O” – shape bending equipment](image9)
1-Punch, 2- Die, 3, 4 – Guidings;

![Figure 10: „O” – shape bending equipment (in the reality)](image10)

![Figure 11: Mechanical expander – Courtesy, Corus Tubes, UK](image11)
Equipment execution assumes the following the same process [6]:

- Drawing up the technical drawing;
- Choosing the material;
- Cutting;
- Cleaning;
- Assembly;
- Quality control;

Technical drawing is performed by specialized software AutoCAD 2013 (student version) [8]. Technical expander is represented by four arms with semicircular plates welded at the ends.

The operating principle is the following: mechanical expander transmits radial oriented internal wall pressure, produced by the hydraulic press.

After designing, is obtained mechanical expander, as shown in figure 12.

**Figure 12: Mechanical expander (technical drawing)**

According to [13] and to [14] expanding pressure for DN400 pipe is 21 MPa. From this reason, axial compressive force that will be applied to one arm is \( F = 200 kN \). Non-deformability of the equipment is a property necessary for correct assessment of the manufacturing process. It follows that arms section dimensions and joints are oversized. Arms section dimension is 30 mm x 20mm, as shown in figure 13, and joint dimension is \( \varnothing \) 22 mm, as shown in figure 16. Here in, yield strength for X 60 steel is \( \sigma_Y = 478 MPa \) [15].

Given the complexity of the equipment, it is necessary to perform strength calculation of the arms and joints (hinges). Must be mentioned, that arms and joints are executed from X60 steel, because the physic-mechanical properties of the steel, are known.

Based on expander drawing, the elements that transmit loading to pipe wall are the next:

- Arms - 4 pieces;
- Joints – 8 pieces (2 pieces per arm)

Considering expander action, arm is loaded by combined loading (axial compression and bending). Based on this principle, for strength calculation, arm is considered double – articulated. Arms material is the X60 steel (same with pipe material).
Figure 13: Arms section
For strength calculation, physical model is presented by double articulated beam, as shown in figure 14.

Figure 14: Schematization of loaded beam
It is observed that number of unknown reactions is greater than number of equilibrium equations it means that the system is indeterminate. According to [16], solving of this problem involves using force method. The basic idea of this method is to identify the redundant forces first - $X_1$. Then using the compatibility conditions, determine the redundant forces. This way the structure is essentially reduced to a statically determinate structure [16].

Remaining reaction is determined using the equations of equilibrium.

Figure 15: Force method for indeterminate system
\( M_{12} = 0 \)  
\( M_{23} = -141x_{23} \rightarrow x_1 = 0 \rightarrow M_2 = 0 \)  
\( x_2 = 0,054 \rightarrow M_3 = -7,614; \)

\( m_{12} = 1x_{12} \rightarrow x_1 = 0 \rightarrow m_1 = 0 \)
\( x_2 = 0,054 \rightarrow m_2 = 0,054; \)

\( m_{23} = 1(0,054 + x_{23}) \rightarrow \)
\( x_1 = 0 \rightarrow m_2 = 0,054; \)
\( x_2 = 0,054 \rightarrow m_3 = 0,108; \)

\[ \delta_{11} \cdot X_1 + \delta_{1p} = 0 \]  \( (15) \)

\[ \delta_{1p} = \frac{1}{E I_y} \int_0^{0,054} -141x (0,054 + x)dx \]  \( (16) \)

\[ \delta_{11} = \frac{1}{E I_y} \int_0^{0,054} x^2dx + \frac{1}{E I_y} \int_0^{0,054} (0,054 + x) (0,054 + x)dx; \]  \( (17) \)

\( X_1 = -\frac{\delta_{1p}}{\delta_{11}} \rightarrow X_1 = 49 kN \)

After redundant \( X_1 \) calculation, it is possible to determine beam stresses.

\[ \sigma_{comb} = -\sigma_N \pm \sigma_{M_y}; \]

\[ \sigma_{comb} = - \frac{N}{A} \pm \frac{M_y}{W_y} \leq \sigma_y \]  \( (18) \)

where:
\( \sigma_N \) – stresses resulted from compression, MPa;

Figure 16 Loading diagram for expander arm
\sigma_{M_y} - \text{stresses resulted from bending, MPa;}
\nonumber
A - \text{arm section area, mm}^2;
\nonumber
N - \text{axial force, N;}
\nonumber
M_y - \text{bending moment, Nmm;}
\nonumber
W_y - \text{section modulus, mm}^3;
\nonumber
\sigma_{comp} = \frac{-141 \times 10^3 N}{600 mm^2} - \frac{0.986 \times 10^6 N mm}{3000 mm^3} = | -328 | MPa < \sigma_Y; \quad (19)
\nonumber

After arms strength calculation, next step follows joints verification. For strength calculation, physical model is presented by rivets loaded by compressive force. During compressive force acting in rivets body appears bearing and shearing stresses, as shown in figure 16.

\text{Figure 17: Rivet loaded by compressive force}

According to [17] in rivets body, shear stress \( \tau \) is equal \( \tau = \frac{F}{n \cdot d \cdot t} \) and bearing stress \( \sigma_b \) is equal \( \sigma_b = \frac{F}{n \cdot \frac{\pi d^2}{4}}. \) Next is presented stress calculation:
\nonumber
\tau = \frac{F}{n \cdot \frac{\pi d^2}{4}} = \frac{200 \times 10^3}{2 \cdot 2.2 \times 22} = 131 MPa < \tau_Y \quad (20)
\nonumber
\sigma_b = \frac{F}{n \cdot d \cdot t} = \frac{200 \times 10^3}{2.22 \times 20} = 227 MPa < \sigma_{Yb} \quad (21)
\nonumber

Materials are cut using abrasive water jet cutting machine MAXIEM 1530 [10].

After designing, material choosing, cutting follows the equipment assembling using welding. Obtained result is presented in figure 18.
7. Conclusion

Manufacturing of the longitudinal seam welded large diameter pipe represents a manufacturing process using complex and large dimensional equipments. Inspection steps from the manufacturing process like, X-ray, ultrasonic, magnetic particle, highlight the surface and body defects.

A major influence on pipe stress and strain state represents residual stresses that remains after each technological step.

Equipment presented in this paper simulate entire manufacturing process and through optical non-destructive testing method - digital image correlation offer possibility to follow evolution of the stress and strain state, as shown in figure 20.
8. References

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