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BENDENABILITY LIMITS IN THREE-ROLL TUBE BENDING

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ABSTRACT

Three-roll tube bending is one of the cheapest technological processes. Nevertheless, during deformation a lot of problems occur which alter the quality of the bending zone. An experimental work and a numerical simulation are used to analyse the influence of process parameters, such as tube thickness, material and bending angle, on bendenability, assessed through the study of the principal defects in three-roll bending, such as ovalization, buckling, springback, wall thickness variation. The results could be used for improving the three-roll tube bending process and get the possibility to find new ways to improve this bending process.

KEYWORDS: tube bending, three-roll tube bending, modeling, FEM, ovalization, buckling, springback

1. INTRODUCTION

The tube bending technology is ubiquitous in all industries, from the aeronautical field to the automotive industry through the oil industry.

The most used bending process in industry is rotary bending, as it is the most effective in obtaining good quality bending. A second interesting process in tube forming is three-roll bending, a cheaper process, which has to be optimized because of more important problems than rotary bending. To optimize this process, tube bending and its occurring phenomenon have to be studied accurately. A lot of studies have already been done on the issue. These studies are based on simulations on FEM (Finite Element Method) software and physical tests in laboratories. Studies let to define process limits concerning tube thickness, bending angle, or bending radius. Some problems, such as tube ovalization, are studied to optimize tube bender machines.

Mei Zhan, He Yang and Liang Huang [1] investigated a numerical-analytic method for quickly predicting springback of numerical control bending of thin-walled tubes. They studied rotary bending on an alloyed aluminum tube and their numerical model followed the Krupskowsky law.

Levent Sözen, Mehmet A. Guler, Recep M. Görgülüarslan and Engin M. Kaplan [3] carried out research on the prediction of springback in the tube bending process based on forming parameters. They also studied rotary bending on an alloyed aluminum tube, with LS-Dyna for the numerical study.

C. Thinvongpituk, S. Poonaya, S. Choksawadee and M. Lee [7] studied the ovalization of thin-walled circular tubes subjected to bending. In their study, the tube is just fixed on its two extremities and bent.

All these studies tried to understand and improve tube bending phenomena and processes and show that tube bending is a difficult research subject.

In the present paper, experimental work and a numerical simulation are used to analyse the influence of process parameters on bendenability, assessed through the study of the principal defects in three-roll bending.

2. PROCESS CHARACTERIZATION

The tooling for roll bending consists of three rolls of the same size disposed as shown in Figure 1. Two inferior rolls are fixed and they are freely rotating around their axes while the third (center) roll is vertically movable. The tube is placed on the two inferior rolls and the center roll is lowered onto the tube. This bending technique is usually employed for bending tubes of large radius.

During the bending process the tube undergoes considerable in-plane distortion such as: ovalization, wrinkling, variation in wall thickness, springback and fracture.

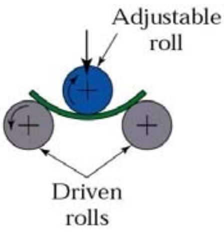

Fig. 1. *Three-roll bending process*

Variations in wall thickness are the result of different stresses induced during the bending process by the axial forces in the inner and outer fibers. The inner and outer fibers are subjected to compressive and tensile stresses, respectively. This results in the thinning of the tube wall at the outer section (extrados) and the thickening of the tube wall at the inner section (intrados). Figure 2 presents the tube parameters.

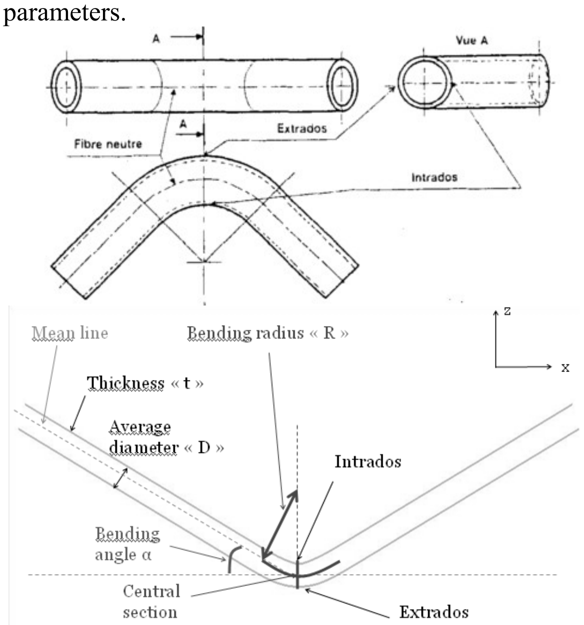

Fig. 2. *Parameters of the deformed tube*

Fracture appears in the fibers at the extrados when the tensile stress induced in the tube due to the bending moment exceeds the ultimate strength of the material.

Wrinkling appears due to compressive stress in the inner surface of the tube. When the tube is bent into a tight radius, it is subjected to high compressive stress in the intrados which leads to its wrinkling (buckling). Wrinkles are wavy types of surface distortion, are unacceptable and should be eliminated.

Ovalization (cross-section distorsion) is a result of the tendency of fibers at both ends to move towards the neutral axis. The outer fiber of the tube tends to move towards the neutral plane to reduce tensile elongation. This results in the cross section of the tube being no longer circular but becoming oval. The oval distortion grows stronger if thinner tube walls and smaller bending radii of the work piece have been selected.

Springback is the result of the unloading of the internal residual stresses developed in the tube after bending. The tube springs back until the internal bending moment drops to zero.

3. EXPERIMENTAL ANALYSIS

The device for the experimental analysis of three-roll tube bending is presented in Figure 3. It was mounted on a 20t hydraulic press. The distance between the two rolls is 200mm and they can rotate freely around their axes. The rolls have 100mm diameters and a circular profile with a radius of 10mm.

The punch roll (superior roll) has the same dimensions as the other two rolls and, during the deformation process, has a speed of 100mm/s. Two vertical displacements for the punch were used: 50mm for tube thickness t=1 mm and 80mm for t=2.3mm.

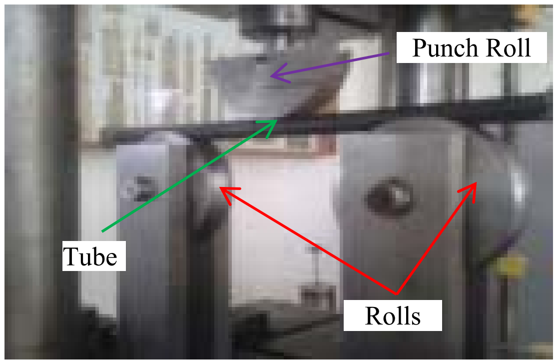

Fig. 3. *View of the experimental device for three-roll bending*

Steel tubes, with 15mm in diameter, 500mm long, and 1mm thick and copper with a thickness of 0.5mm were used.

The appearance of wrinkles during the experiments was observed. For copper tubes, wrinkles appeared at a bending angle of 5.45 degrees, the depth between the extrados and the intrados, on vertical direction, being of 12.13mm. In this case, this undesirable phenomenon appears as a result of the difference between the tube diameter and the radius of the circular profile of the punch roll. In the first stage of deformation, the tube sides are unsupported, the ovalization appears and finally the tube will winkle (Figure 4).

Fig. 4. *Wrinkling of the copper tube*

There are three phases in the evolution of the center section of the pipe during the three point pipe bending process: firstly, a linear phase, with a circular section (very short); secondly, the ovalization phase because of plastic deformation (material non linearity), the initial circular section becoming elliptic; thirdly, the buckling phase, when flatting of the intrados appears, with waves following the x axis (high waves) and the y axis (little waves).

4. NUMERICAL MODEL

Nowadays simulation using FEM is the main method for the investigation of deformation processes, including bending, in terms of strain and stress analysis, forces prediction and formability evaluation.

Figure 5 presents the model of the tool used in simulation.

For the tool components, a rigid material is used, *Mat_rigid (Mat 20), according to the Dynaform software. Consequently, the elastic deformation of the tool is assumed to be negligible compared to the plastic deformation of the tube.

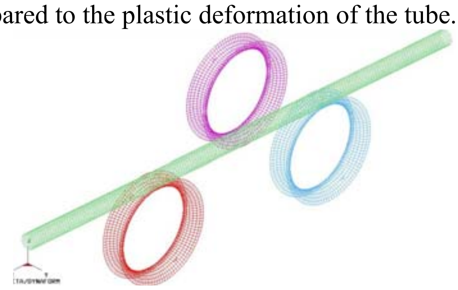

Fig. 5. *Tool model used in three-roll bending process simulation*

The blank is a tube (Φ15x500mm) made of steel, with thicknesses of 0.5mm, 1mm, 1.5mm, 1.75mm, 2mm and 2.3mm, respectively.

Two types of material were used: steel and copper. The materials for tubes have a "power" sort of behaviour:

$$\sigma = \sigma_0 + K \cdot \varepsilon^n \qquad (1)$$

where: K is the strength coefficient, K = 370 MPa for steel and K = 654.57 MPa for copper; n – strain hardness exponent; $n = 0.41$ for steel and $n = 0.57$ for cooper; $\sigma_0 = 176$ MPa for steel and $\sigma_0 = 347$ MPa for copper.

In the simulated model, the tube was modelled using 3D thin shell elements with the Belytschko-Tsay element formulation, with five integration points through the thickness.

The interfaces between the outer layer of the tube and the rolls were modelled with a contact algorithm type Contact_forming_ surface_to_ surface. The friction coefficient was considered equal to 0.125.

The punch roll which deforms the tube is moving vertically, with a speed of 100mm/s. Inferior rolls are rotating around their axes.

For a bend angle of 5.45 degrees, the tube image obtained by simulation is presented in Figure 6. Wrinkling is present.

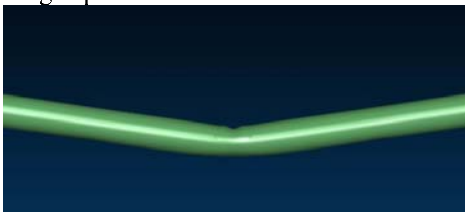

Fig. 6. *Geometry of the modeled part bent*

5. RESULTS ANALYSIS

5.1. Ovalization

At the beginning, the central section is circular. After deformation, the section could take the form presented in Figure 7.

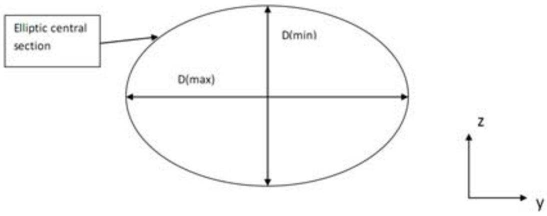

Fig. 7. *Schema of the ovalized and elliptic central section*

During the bending process, the central section is deformed and takes an elliptic form named ovalization phenomenon.

The degree of ovalization is defined as***:***

$$\varsigma = \frac{D\,max - D\,min}{D} \cdot 100 \qquad (2)$$

where: D is the initial tube diameter; Dmax – maximum tube diameter; Dmin – minimum tube diameter.

Figure 8 presents the ovalization of the central section of the steel tube (t=1mm) for three different bending angles.

The ovalization of the central section leads to instability and a local collapse in this section.

This local buckling appears like a flattening of the central section on the intrados.

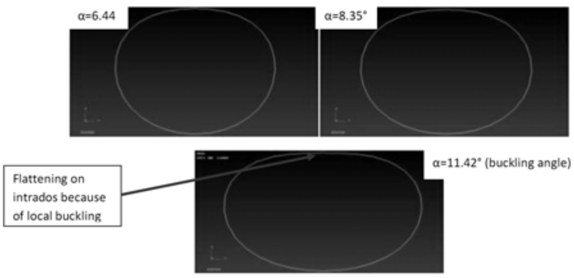

Fig. 8. *Progressive ovalization of the central section leading to local buckling*

The ovalization degree was measured for different thicknesses, on steel, calculated with formula (2), and is presented in Figure 9. By increasing the tube thickness, the degree of ovalization will decrease.

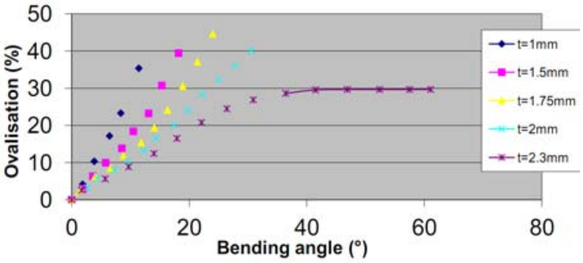

Fig. 9. *Ovalization variation with bending angles for several thicknesses*

It appears like an exponential evolution of the degree of ovalization leading to a local buckling for 1, 1.5, 1.75 and 2mm of thickness. But for 2.3mm of thickness, an asymptotic limit of the ovalization degree appears at about 29.5%.

It appears that ovalization before buckling increases linearly when the bending radius increases. This means that the increase of the bending radius allows the reduction of the ovalization degree.

The ovalization could be evaluated accordingly with [2], based on the energy of deformation:

$$\varsigma = \frac{a^4}{R^2 t^2} \tag{3}$$

where: a is the initial tube radius; R – actual radius; t – thickness. When thickness increases, the ovalization degree decreases; that means that the pipe does not need to be deformed a lot to reach a minimum of energy of deformation. In cases where buckling occurs, the ovalization degree cannot reach ς and buckling occurs before.

The comparison between the ovalization degree in the theoretical formula (3) and the numerical measurements, for t=2.3mm is presented in Figure 10.

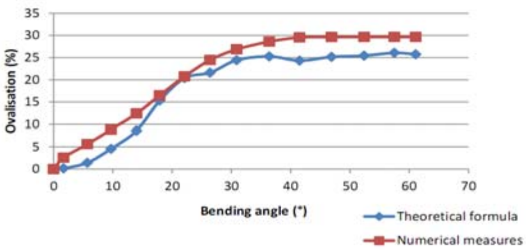

Fig. 10. *Ovalization variation with bending angle for 2.3mm thicknesses*

The numerical results give a good approximation of the ovalization degree with theoretical formula (3), with a small difference (about 3.8% for t=2.3mm).

5.2 Buckling

The buckling phenomenon occurs because of a too high ovalization degree. The increase of the bending radius leads to the reduction of the ovalization degree. That is why it lets to get larger bending angles before reach buckling.

Figure 11 shows the evolution of the maximum bending angle reached before buckling (t=1mm) following four ratios between the punch radius and the deformed tube diameter (R(punch)/D): 1.5, 3.33, 4, and 5.

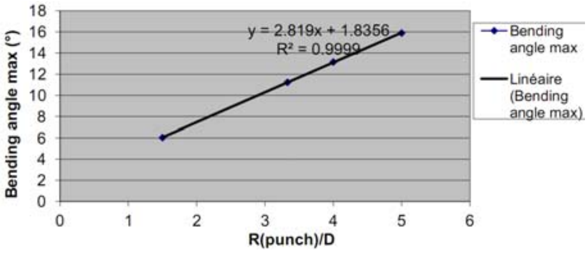

Fig. 11. *Maximum bending angle reached before buckling*

The dependence of the bending radius to the bending angle makes it difficult to get, at the same time, the desired bending radius and the desired bending angle for low bending angles. This is an important problem with this process, which does not exist in rotary bending because, during the process, the tube "enrolls" the die and so adopts its radius during the process. Keeping a constant bending radius from the beginning of the process seems to solve a lot of problems in tube bending.

Figure 12 shows the variation of the maximum bending angle function of thickness before buckling. By increasing thickness, the value of the maximum bending angle will increase.

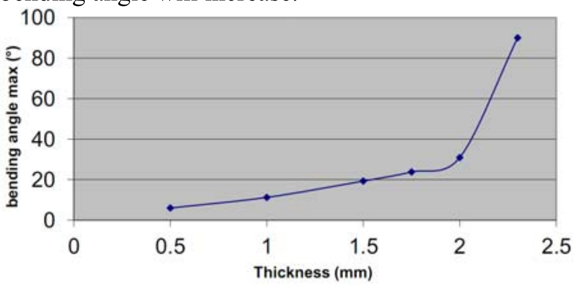

Fig. 12. *Variation of the maximum bending angle reached before buckling with thickness*

Waves appear just after buckling and their theoretical plastic wave length is [4]:

$$\lambda(theo\_plas) = 2\pi\sqrt[4]{12(1-\nu^2)}\sqrt{at}\sqrt[4]{\frac{Es}{Et}\left(\frac{1}{4}+\frac{3Et}{4Es}\right)}\cdot 0.135 \tag{4}$$

where: Es is the secant modulus, Et the tangent modulus, ν the Poisson's ratio, t the thickness and a the average pipe radius. Let's suppose a>>t, a = 7.5mm, Et = 5000 MPa and Es = 904 MPa.

The following graph (Figure 13) shows the wave length following thicknesses from the theoretical formula (4) and numerical measurements:

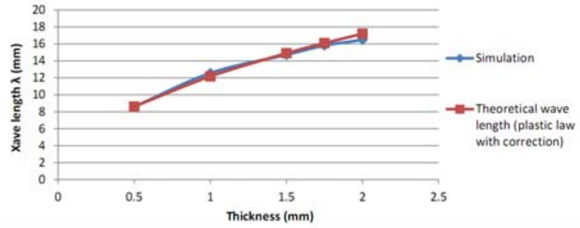

Fig. 13. *Variation of the wave length with thickness*

5.3. Thickness variation

The evolution of thickness along the tube axis (on the intrados) lets to show waves (Figure 14).

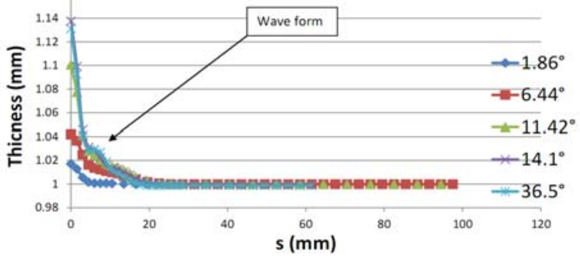

Fig. 14. Thickness variation along the tube axis for several bending angles

On the intrados of the central section, thickness increases and decreases quickly until 20mm.

On the contrary, on the extrados, thickness decreases. Figure 15 shows the evolution of thickness with θ, on the intrados, where θ has the significance presented in Figure 16.

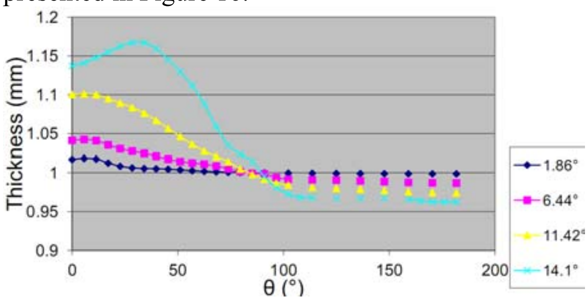

Fig. 15. *Thickness variation with angle θ*

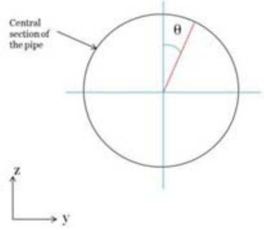

Fig. 16. *Angle θ definition*

On the intrados, the thickness increases more than on the extrados. On the intrados, the graph looks like a sinus until θ = 90°. After 90°, the thickness volves almost like linearly. There is a dissymmetry of the evolution of thickness between the intrados and the extrados.

5.4. Springback

To get the desired bending angle, springback has to be taken in account. Indeed, at the end of bending (in loading), the desired bending angle and radius are reached, but after unloading, these values are modified. The bending angle becomes smaller and the bending radius becomes longer.

The theoretical formula to calculate the springback angle is [3]:

$$\theta_U = \theta_L \left(1 - \frac{R_L M}{EI} \right) \qquad (5)$$

where: θ_U is the angle after unloading; θ_L – angle at the end of loading; R_L – radius at the end of loading; M – the bending moment; I – inertia moment; E – elasticity modulus.

Figure 17 presents the variation of the springback angle with the bending angle, from theoretical formula (5) and the numerical measurements. The figure shows that springback increases with the bending angle.

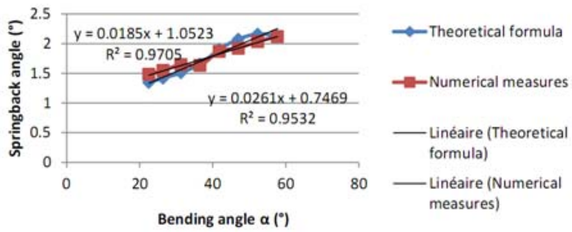

Fig. 17. *Springback angle variation with the bending angle α, theoretical and numerical measurements*

Numerical results are closer to theoretical results according to formula (5). Formula (5) is a good approximation of the springback angle for the bending angles used in the present study.

6. CONCLUSIONS

The paper presents several phenomena occuring in the three-roll bending tube process, which affect the bending quality. The obtained results show that:

- the ovalization has an exponential variation for small thicknesses and an asimpotic evolution for greater thicknesses;
- increasing the bending radius leads to the reduction of the ovalization degree;
- ovalization of the central section of the bend tube leads to instability and consequently to a local collapse in this section (buckling);
- along the pipe, on the intrados of the central section, thickness increases and then decreases, whereas on the extrados, on the contrary, thickness decreases;
- in cross section, on the intrados, thickness has a sinusoidal increasing till 90° and then becomes liniar;

- springback increases with the bending angle and decreases with tube thickness.

The present results could be used for improving the three-roll tube bending process.

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