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ROLE OF FILLING MATERIAL ON DEFECTS OF THIN-WALLED TUBE BENDING PROCESS

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This paper investigates approaches to avoid common defects such as the wrinkling, cross section distortion and changing in wall thickness in the bending process of a thin-walled tube. A series of experimental tests has been carried out by filling the tube with melted lead and different types of rubbers. Firstly, tubes were filled by several kinds of rubbers and bended, but the wrinkling was observed at the inner side of the tubes. Also the cross section distortions happened to be above the acceptable range. Therefore, rubbers could not be a suitable filling material for steel tubes. As the second case, lead was used as the filling material to avoid the defects. For this purpose, the tubes were filled by liquid lead and it was solidified to form a leady core to support the inner part of the tube bend. After the bending process, lead is melted and removed. This removable leady core was called the 'Leady Lost Core'. To study the process numerically, a 3D finite element model of the horizontal bending process has been built using a commercial code. Experimental tests have been carried out to verify the simulation results and developed to provide additional insight. To consider the friction coefficient, in this work, "The Barrel Compression Test" method has been used. Comparisons between the experimental and finite element results have shown remarkable agreement. They show that wrinkle initiation and cross section distortion can be avoided with a lost core of low temperature melting metal like lead or tin.

Key word: thin-walled tube; bending process; low temperature melting metal

1. Introduction

In recent years, curved tubular parts have appealed more applications in automobile, aerospace, oil industries where high strength/weight ratio elements are needed (Manabe and Amino, 2002; Koc and Altan, 2001). The defect due to a tube bending process is a very important matter and it should always be avoided. There are some parameters to be controlled in order to reduce the defects. For example, geometry parameters of tubes, wall thickness, outer diameter-to-wall thickness ratio D/t, centerline bending radius-to-outer diameter ratio R/D and friction conditions are some of these parameters which are usually modified to maintain the instability. In the tube forming process, the wrinkling and variation in the wall thickness and cross section distortion are the common defects. The wrinkling often happens in the inner part of the bending tube, while the cross section distortion happens in the outer part, which should be avoided.

Up to now, many researches have dealt with the thin-walled tube bending defects, but only few of them included both numerical and experimental results. Tang (2000) explained seven phenomena in tube bending and also mentioned their practical formulas. Yang *et al.* (2006) investigated the effect of frictions on cross section quality of thin-walled tube NC bending, Yang and Lin (2004) studied the wrinkling for forming the limit of tube bending processes, Guarracino (2003) analysed cylindrical tubes under flexure. Li *et al.* (2006) carried out a research on a new method to accurately obtain the wrinkling limit diagram in the NC bending process of a thin-walled tube with large diameter under different loading paths.

There are many methods to avoid defects in the tube bending process such as using sand filling. The rubber filling method has been reported as a numerical study by Baudin *et al.* (2004). Lee *et al.* (2005) used an oval tube to reduce the cross section distortion. Jiang *et al.* (2011) used the three-dimensional finite element method to investigate deformation behavior of medium-strength TA18 high-pressure tubes during NC bending with different bending radii. They showed that the cross-sectional deformation and the wall thickness variation during bending in small bending radius are clearly different from those using a normal bending. Tian *et al.* (2013) mainly studied the effects of geometrical parameters on wrinkling of rectangular wave-guide tubes by using a 3D-FE model for rotary-draw bending processes. Zhang *et al.* (2011) experimentally studied bending characteristics of a large diameter thin-walled CP-Ti tube in rotary draw bending. Wang *et al.* (2012) numerically and experimentally studied the effects of internal pressure on forming defects, corner radius and thickness distribution of 5A02 aluminum alloy shear hydro-bending tubes.

In the present study, experimental and numerical works have been carried out to investigate how to avoid the defects in thin wall tubes under bending by filling with materials such as pure lead and rubber. As a relevant work, Ohashi *et al.* (2001) used a low temperature melt alloy in the bulging process for hollow products.

In this paper, firstly a series of experimental tests was implemented by filling the tubes with three different types of rubber and lead. Figure 1 shows a schematic presentation of the whole experimental procedure explained in Section 2. In Section 3, a numerical investigation has been done, and finally, in Section 4 the results are presented and discussed.

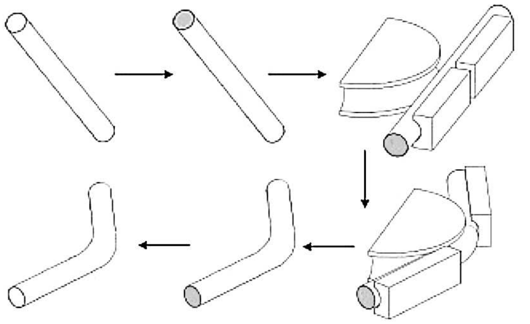

Fig. 1. Sketch of the tube bending process with a leady lost core

2. Experimental setup

On experiment has been performed to provide a general concept of the tube bending process and to verify FE modeling results. A hydraulic ram bending nachine was used as shown in Fig. 2.

2.1. Using rubbers as filling materials

Three kinds of rubber were used as the filler inside the tube to support the inner side of the tube. Firstly, a tube filled by natural rubber and was bent. After bending, severe wrinkling was observed (Fig. 3a) at the inner side of the tub. Also, cross section distortion appeared to be above the acceptable range. Then, as the second test, a type of red polyurethane rubber was used (Fig. 3b). But like in the previous test, the result was poor and the wrinkling and cross section distortion occurred. Finally, white polyurethane was tested as the filler and the wrinkling defect was reduced, but the bending quality was not still acceptable, see Fig. 3c. Therefore, lead metal was considered as the filler, which will be explained in the next Section.

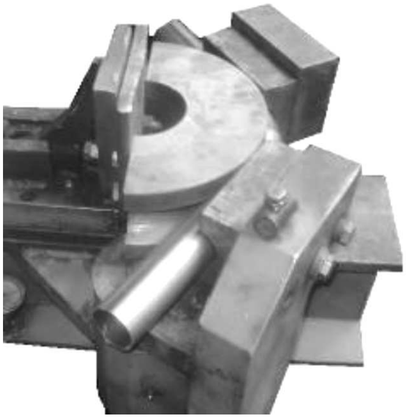

Fig. 2. The specimen in the ram bending machine

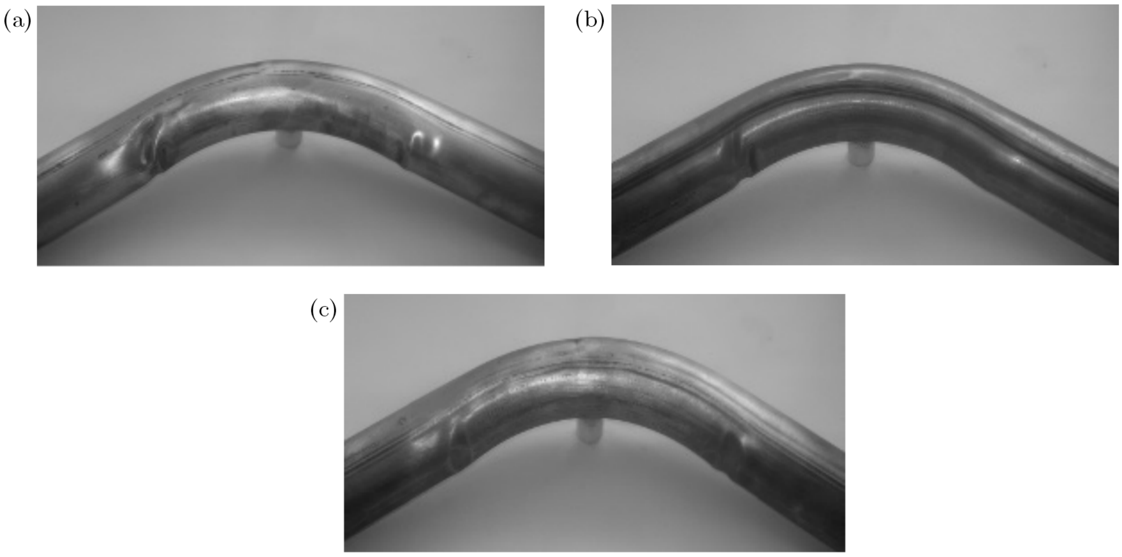

Fig. 3. Tube filled with (a) natural rubber, (b) red polyurethane, (c) white polyurethane

2.2. Using lead as the filling material

In this method, the tube was filled by a liquid made of a low temperature melting point metal such as pure lead prior to bending of the tube. Then the liquid was solidified and after the bending, the tube was heated up to melt the core to be removed. The leady core can support the inner part of the tube. This removable leady core is called the ‘leady lost core’. All the experimental results of the tests will be discussed in Section 4.

3. FE Simulation

3.1. Material properties and geometry

A uniaxial tensile test was used to determine mechanical properties of the tube made of Steel-USt37 and a pressure test to extract lead properties. These properties are listed in Tables 1 and 2. The hardening behavior can be described by using the equation $\sigma = K(\varepsilon)^n$.

The Cloumb friction model is used in the simulation process. The friction coefficient between the tube and clamp die and between the tube and rotary dies are equal to 0.15. Bulk forming was assumed for the lead forming. “Barrel Compression Test” (Ebrahimi and Najafizadeh, 2004)

Table 1. Mechanical properties of tube

Poisson's ratio	0.3
Maximum elongation [%]	44.2
Elasticity modulus [GPa]	210
Yield stress [MPa]	270
K	345
n	0.05

Table 2. Mechanical properties of lead

K	28.26
n	0.175
σ_y [N/mm^2]	25
σ_{uts} [N/mm^2]	29
E [GPa]	14
Poisson's ratio	0.3

has been carried out to find the magnitude of the friction factor m. The corresponding friction coefficient m has been obtained by using the equation introduced by Hwang and Tzou (1997). Figure 4 shows the lead cylinder after deformation by 'Barrel Compression Test' to determine the friction factor between the lead and tube. The obtained friction coefficient between the tube and lead is equal to 0.043.

Fig. 4. leady cylinder after deformation by "Barrel Compression Test" for measurement of the friction coefficient

The circular tubes (made from Steel-USt37) with diameter $D_0 = 50$ mm, wall thickness of $t_0 = 1.5$, 1.25, 0.09 mm, bending radius 150 mm and bending angle 45° were used in all experiments.

3.2. FE modeling

A 3D finite element model has been built using ANSYS software. For the model, a 4-node 3D space shell element for the tube model (shell 143), a 20-node 3D space solid element for the core model (solid 95) and three-dimensional rigid elements for the dies models have been used. All dies and tube geometrical parameters were the same as in the experimental specimen. In the tube bending process, there are three contact surfaces between the tube/bend die, tube/rotary dies and tube/leady core. The "Surface-to-surface contact" method has been employed to describe the mechanical constraints for different contact pairs using CONTACT174 and TARGET169.

4. Results and discussion

In order to investigate the effects of the filling material on defects, a set of experimental and numerical FE runs have been implemented and compared. In one of them, a hollow tube was bent and another one was a filled tube. The difference between the experiment and simulation shows an error equal to 10%.

4.1. Effect of the leady lost core on wrinkling

FE simulation and experimental results are shown in Fig. 5. It presents two tubes which have been bent with the filler (leady lost core) and without filler. The tube with the core is

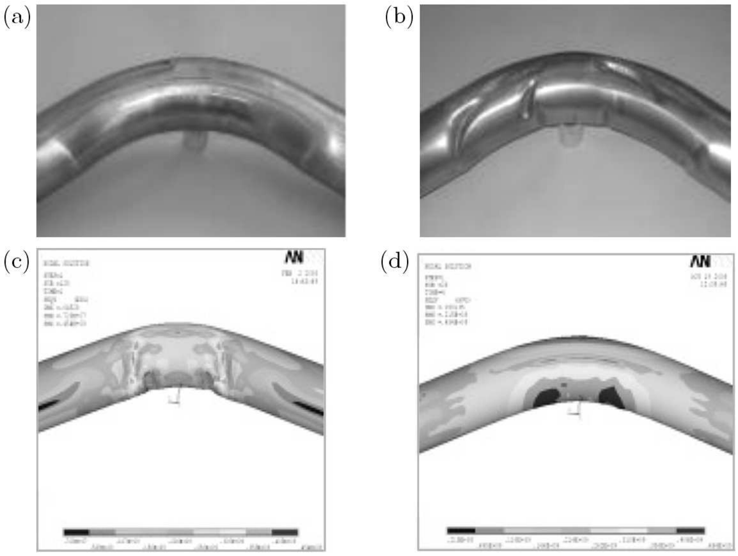

Fig. 5. Comparison of finite element analysis and experimental results; (a) experimental test for the tube filled with lead, (b) experimental test for the tube without filling material, (c) FE simulation result for the tube filled with lead, (d) FE simulation result for the tube without filling material

perfect without any wrinkling but in the tube without the core severe wrinkling occurred. Based on the explanation presented by Li *et al.* (2006), regarding the stain energy principle, it can be emphasized that the critical moment of the wrinkling onset happened when the internal energy of the wrinkled shell U is equal to the work done by the external forces T. It can be concluded from Fig. 5 that the filler causes the internal energy of the wrinkled shell to be increased and the wrinkling phenomenon not to occur.

4.2. Effect of the leady lost core on cross section distortion

Figure 6 shows the cross section distortion in tubes under bending with and without the leady lost core. It shows that the cross section distortion occurs in the tube bent without the

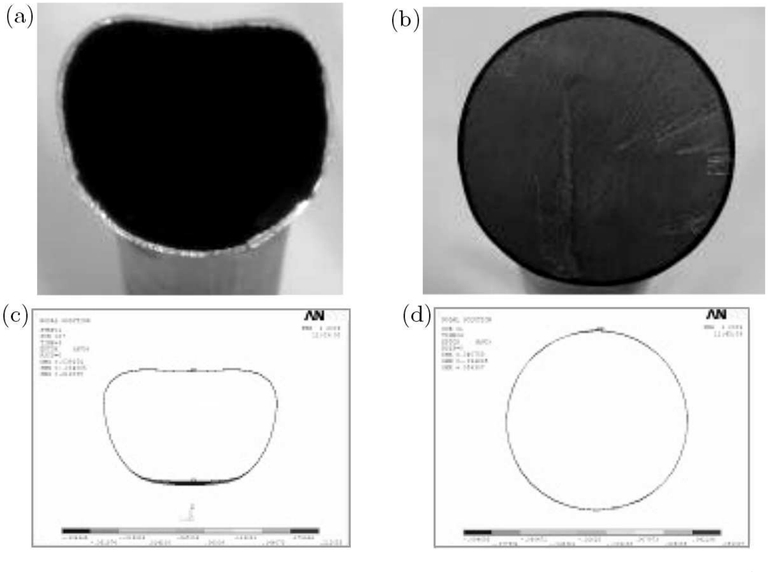

Fig. 6. Comparison of the tube cross section with and without the lost leady core; (a) experimental test for the tube without filling material, (b) experimental test for the tube filled with lead, (c) FE simulation result for the tube without filling material, (d) FE simulation result for the tube filled with lead

filler. The tube with the core has a quite prefect circular cross section without any distortion after the bending process. Also it shows that the FE and experimental results are the in a good agreement.

4.3. Effect of the leady lost core on changing the wall thickness

In Table 3 FE simulations and experimental results for the extrados and intrados wall thicknesses at the bending zone are compared. It can be seen that the wall thickness outside the bending is always decreased, but when the tube is filled by the leady lost core, the thinning value of the extrados wall thickness is increased. It can be found that the thinning in the filled tube is more than 5% higher in comparison with the non-filled tube. Also, Table 3 shows that the wall thickening of the filled tube is about 2% less than for the non-filled tube. Figure 6 shows that the filling material decreases the movement of neutral axis, so it increases tension in the outer side of the tube and decreases the compression in the inner side of the tube. Consequently, the outer wall thickness increases, while the inner wall thickness decreases.

Table 3. Comparison of wall thickness variations

		Extrados wall thickness	Intrados wall thickness
Filled	Experimental	1.2	0.915
	Numerical	1.059	0.905
Non-filled	Experimental	1.14	0.9
	Numerical	1.04	0.91

5. Conclusion

This study deals with the making use of a low temperature metal as the filler inside a tube during the thin-walled tube bending process. A 3D FE model and experiments have been conducted to study the effect of the filler on wrinkling, cross section distortion, wall thinning and thickening. The results of nonlinear FE analysis have been verified by experimental results. According to the results of this research, it can be concluded that:

- If the rubber core is used inside the tube, the wrinkling phenomenon and cross section distortion could be reduced, but they could not be completely avoided in the steel tube.
- If a low temperature metal filling material is used inside the tube, the defects such as wrinkling and cross section distortion can be completely avoided.
- Using a filling material increases the inner-tube energy and, consequently in accordance with the low energy, it can prevent the wrinkling phenomena.
- The filling material decreases the movement of neutral axis toward the inner part of the bending and, therefore, it increases tension in the outer side and decreases compression in the inner side of the tube. As a result, the outer wall thickness undergoes reduction, while the inner wall thickness decreases.

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