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Research Note

Optimization of Working Conditions During Push Bending Process

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Thin-walled tube bending has found many its applications in the automobile and aerospace industries. This process may produce a wrinkling, bulking and tearing phenomenon if the process parameters are inappropriate, especially for tubes with large diameters and thin wall thicknesses. Push bending process is one of the methods used for bending tubular parts. It is a suitable technique to make considerably small bending radii. The method is performed using a rigid die to guide and form the tube into the required shape while the tube is pushed by a punch. A pressure media is used inside the tube to prevent its wrinkling and buckling. Hyper-elastic (rubber) materials are commonly used as the pressure media. This paper presents the pressure distribution within the tube, before and during the push bending process. Theoretical result of pressure distributions is compared with the finite element simulations. Effects of rubber properties on the tube quality are also studied. Finally optimum working conditions of process is predicted by the finite element method and is compared with previously published experimental observations.

NOMENCLATURE

D_0	Tube diameters
E	Young's modulus
E_{rr}	Relative error measure
I_1, I_2, J	Strain invariants
N, C_{ij}, D_i	Material parameters
S_{ut}	Ultimate tensile strength
t_0	Sheet thickness
T_i^{test}	Stress value from the test data
ρ_0	Maximum internal pressure
μ_2	Friction between rubber and the tube
ε_i	Nominal strain
λ_i	Stretch in the loading direction

INTRODUCTION

Manufacture of bent tubes plays a very important role in various fields of aerospace, petroleum, power systems, tube and pipe engineering and so on. Today's modern aeroplanes require high strength-to-weight ratio of components to satisfy the aeroplane's flight performance requirements. Thin-walled tubes with high strength such as 304 stainless steel, Al-6061 and titanium are the components used in the hydraulic and fuel piping of airplanes [1]. A suitable bending method should be selected based on the tube material, relative bend radius (R/D), relative thickness (t/D) and desired precision, where D is the outside diameter, R is the centerline bending radius and t is the wall thickness of the tube.

The bend radius of tubes should be preferably several times bigger than the tube diameter, and if a small bend radius of about the tube diameter is needed, it would be very difficult to make it with common cold-bending methods. In such hard bending conditions, the push bending method can be used to make the tube with a small bend radius [2].

Push bending method bends, thin wall, stainless steel or AL60-61 tubing on radii down to 1D. This tube possesses a combination of light weight and high stiffness, which has attracted many applications in the aerospace [3].

Push bending process is one of the tube-bending

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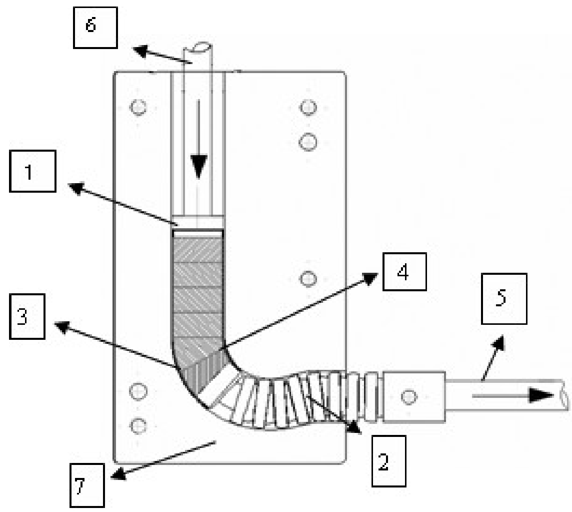

Figure 1. The push-bending principle in the forming of a small bend radius tube. (1) The plunger, (2) Mandrel, (3) The rubbers, (4) The thin-walled tube, (5), (6) Hydraulic cylinders, (7) The die.

methods that can be used prior to the hydro-forming processes. If the bending process is performed incorrectly, tearing may occur in the next hydro-forming process [4-6].

Several types of defects may occur during a push bending process; accordingly, a fairly complex process control is required for forming a sound bent part. Wrinkling on the inner side of thin-walled tubes, tearing and/or thinning of the outer side of the bend zone, upsetting and buckling in the straight part of the tube are among the problems that may occur in the push bending process. Rubber is used in a push bending process to control the metal flow by applying internal pressure within the tube. It will be shown in this paper that in order to achieve successful bend, several complexities are encountered in obtaining suitable operating conditions. For example, rubber properties should not be uniform. Hard rubber bars should be used at both ends and soft rubber bars at the middle to make a sound defect-free bend. The process is also highly sensitive to friction conditions of the inner and outer surfaces of the tube.

In this article pressure distribution within the tube is investigated. Two different methods are used. In the first one, a closed form equation is obtained which is based on slab method. In the second approach explicit FEM analyses with automatic surface to surface contact algorithm are used. The results of the two approaches are satisfactorily compared, which validate both approaches. Then using FEM simulations, the push bending process is optimized and appropriate working conditions are suggested. It is shown that fundamental and practical aspects of the process can be better understood and predicted by the FEM simulations.

ESTIMATION OF PRESSURE DISTRIBUTION INSIDE THE TUBE

In a push bending process, the tube is filled with rubber bars, and internal pressure is generated by squeezing the two exposed ends of the rubber bars. For this purpose, a flexible mandrel is used at one end of the tube and a plunger at the other end of the tube, see Figure 1.

Both plunger and mandrel are operated by hydraulic cylinders. Internal pressure drops inside the tube due to friction between the rubber and the inside wall of the tube. Two different methods are used to obtain pressure distributions within the tube. In the first method, a closed form equation is obtained which is based on slab method. In the second approach explicit FEM analyses are used. The results of the two approaches are compared to validate the analyses.

Estimation of Pressure Magnitude by a Closed Form Approach

Maximum internal pressure can be predicted using the following equation [7]:

$$P_0 = \frac{2S_{ut}t_0}{D_0} \tag{1}$$

where S_{ut} is ultimate tensile strength, t_0 and D_0 are sheet thickness and tube diameters respectively. This equation is simply the equilibrium of a thin wall tube at yielding conditions. Based on Eq. (1) and data given in Table 1 [7], P_0 is estimated to be 30 MPa. In other words, 30 MPa is exerted by the flexible mandrel at one end and 30 MPa is exerted by the plunger at the other end.

Pressure Drop Inside the Tube

Because of the friction between the rubber and the tube (μ_2) pressure drops from the tube ends towards the center according the following equation [7]:

$$P = P_0\, e^{-4\mu_2\, x/D_0} \tag{2}$$

Figure 2 shows a slab with pressure Pat a distance "x" from one end of the rubber (point A). Pressure

Table 1. Simulation parameters.

Material	St-304
Young's modulus, E (GPa)	209
Poison's ratio, ν	0.3
Density, ρ (kg/m^3)	7800
Ultimate tensile strength, S_{ut} (MPa)	614
Tensile yield strength, S_{yt} (MPa)	420
Tube initial diameter, D_0 (mm)	40
Tube initial length, L_0 (mm)	180
Tube initial thickness, t_0 (mm)	1
Bend radius (mm)	60
Friction coefficient, (tube-die) μ_1	0.1
Friction coefficient, (Rubber-tube) μ_2	0.3

distributions within the tube before the bending stage are also obtained by the FEM method and are shown in Figures 3, 4. FEM analyses were performed using both axi-symmetric and 3D elements. Then they were compared with the closed form solution obtained by Eq. (2). Figure 3 shows pressure distributions within the tube and at the contact surfaces of the rubber and the tube (The tube and the die are not shown). According to Figure 4, the trends of pressure drops are the same for closed form and FEM methods. In other words pressure distributions predicted by various methods are very similar. However FEM results provide more information about pressure distributions at every point within the rubber.

SIMULATION OF THE BENDING PROCESS

Figure 5 shows the model which is used in the finite element analyses. Half of the part is analyzed due to symmetric conditions. According to Figure 5, the model comprises of:

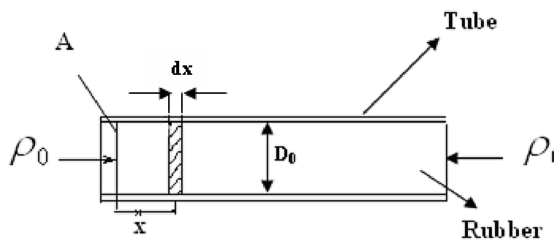

Figure 2. Pressure acting on a vertical element of the tube.

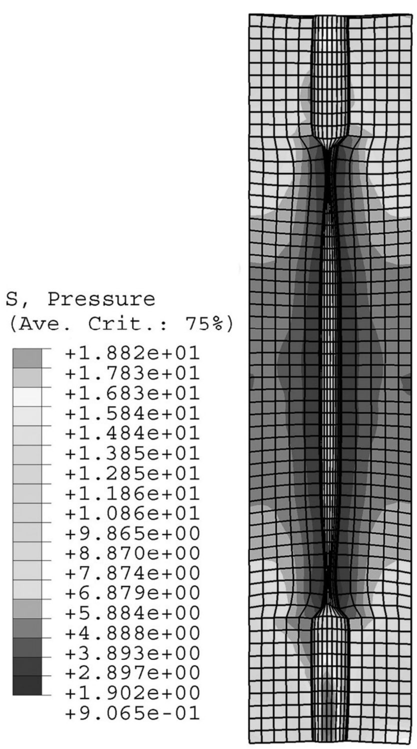

Figure 3. Pressure drop before bending.

1. Rigid die-I, to guide the tube towards the elbow section.
2. Elbow section.
3. Rigid die-II, which is used to guide the mandrel and bent tube.
4. Deformable tube: The tube properties are shown in Table 1.
5. Rubber: A small hole is considered in the rubber. The idea of this hole was to create a space for the elements in the centre of the rubber rod to be squeezed and compressed; otherwise numerical problems may be encountered due to incompressible behavior of the rubber [8].
6. Mandrel which is not considered in the model but its effect is taken into account as a back pressure.
7. Plunger which is used at the feeding end of the tube, not considered in the model and not shown in Figure 5 but its effect is taken into account as a pressure.

In these finite element simulations discrete rigid elements are used for rigid tools. Solid elements are used for the deformable tube and the rubber part.

Solution Stages in the Finite Element Model

The FEM solutions include 2 stages: Stage 1 in which internal pressure is applied to the tube by the rubber and stage 2; bending stage during which the tube is pushed into the elbow section by the punch. Time period for the first stage is 0.2 sec and for the second stage is 2 sec.

RESULTS AND DISCUSSIONS

FEM Simulations of Push Bending Process Using the Mooney–Rivlin Material Model

In order to study the effects of rubber properties, two analyses were performed with two types of rubber; a soft rubber (85 shore-A) and a hard rubber (75 shore-D).

The behavior of rubber materials is hyper elastic and highly nonlinear [9]. Therefore, strain energy potential (U), is used for hyper elastic materials rather than a Young's modulus and Poisson's ratio, to relate stresses to strains. Unlike elasticity, there is no unique form of U for a nonlinear case. Some common forms for U are: the polynomial model, the Ogden model, the Arruda-Boyce model, and the van der Waals model. Simpler forms of the polynomial model are also available, including the Mooney-Rivlin, neo-Hookean, reduced polynomial, and Yeoh models.

The polynomial form of the strain energy potential is used more than other models and will be considered in this analysis. Its form is:

$$U = \sum_{i+j=1}^{N} C_{ij}(I_1 - 3)^i (I_2 - 3)^j + \sum_{i=1}^{N} \frac{1}{D_i}(J-1)^{2i}(3) \tag{3}$$

where, I_1, I_2 and J are the strain invariants and N, C_{ij}, and D_i are material parameters, which may be functions of temperature. The C_{ij} parameters describe the shear behavior of the material, and the D_i parameters introduce compressibility [9]. If the material were fully incompressible, all the values of D_i would be zero, and the second part of the above equation could be ignored.

The material coefficients (C_{ij}) of the hyper-elastic models can be calibrated by ABAQUS using experimental stress-strain data [10]. The material constants (C_{ij}) are determined through a least-squares-fit procedure, which minimizes the relative error measure in stress [10]. For the nominal-stress–nominal-strain data pairs, the relative error measure is minimized, *i.e.*

$$E_{rr} = \sum_{i=1}^{n} (1 - T_i^U / T_i^{test})^2 \tag{4}$$

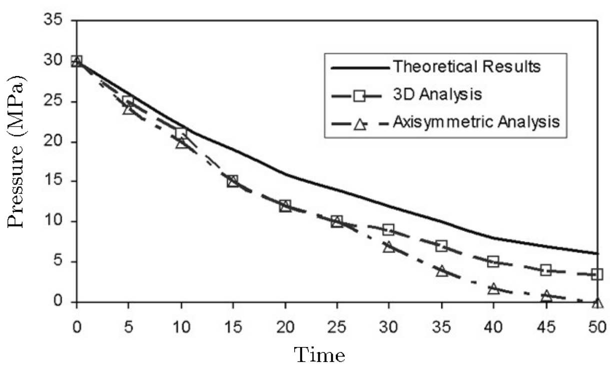

Figure 4. Comparison between FEM analysis and closed form solution.

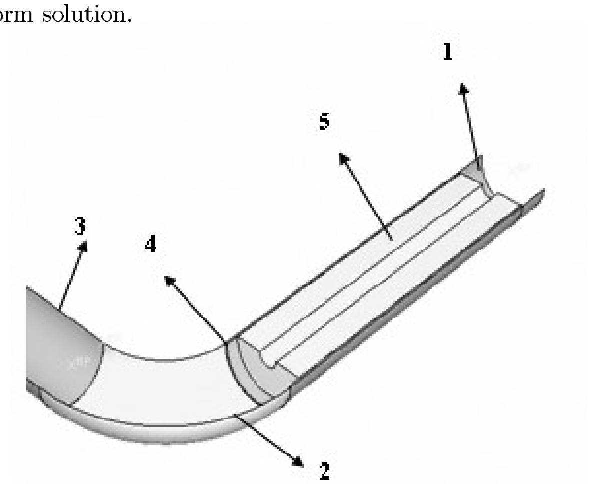

Figure 5. Bending model: 1-Rigid die-I, 2-Elbow section, 3-Rigid die-II, 4-tube, 5-Rubber.

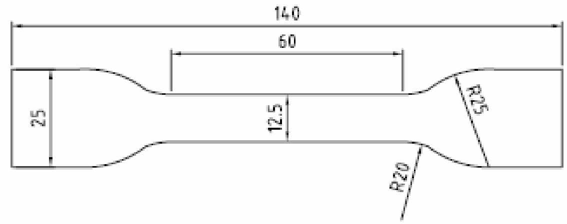

Figure 6. The "dog-bone" specimen used in tension test.

$$\frac{\partial E_{rr}}{\partial c_{ij}} = 0 \tag{5}$$

T_i^{test} is a stress value from the test data, and T_i^U comes from one of the nominal stress expressions derived below:

$$T_i^U = \frac{\partial U}{\partial \lambda_i^U} \tag{6}$$

$$\lambda_i^U = 1 + \epsilon_i^U \tag{7}$$

where, ε_i is the nominal strain and λ_i is the stretch in the loading direction. The uniaxial tension test is the most common test and is performed by pulling a "dog-bone" specimen with standard dimensions as shown in Figure 6 [10, 11].

To obtain a suitable model which can represent the rubber behavior in a push bending simulation, the Yeoh, Mooney- Rivlin and Neo Hooke models were used and compared with each other. According to Figure 7, the Mooney–Rivlin material model gives better results compared to the other two models.

The Mooney-Rivilin model is defined using the strain energy density function:

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{d}(j-1)^2 \tag{8}$$

For the soft rubber, the following constants were obtained:

$$C_{10} = 2.30 \text{ MPa}$$

$$C_{01} = 0.82 \text{ MPa} \tag{9}$$

For small to moderate strains (ε<<1) tensile modulus can be defined as [9]:

$$E = 6\,(C_{10} + C_{01}) \tag{10}$$

Hence, for the soft rubber the elasticity module is equal to 18.7 MPa. For the hard rubber (75 shore-D) the elasticity module is 180 MPa which is approximately 10 times larger than the soft rubber [7]. For the hard rubber it was not possible to make a tensile specimen. According to [9] if it is not possible to prepare a tensile specimen, Eq. (10) and Eq. (11) can be used to determine C_{10} and C_{01}.

$$C_{01} \approx 0.25\,C_{10} \tag{11}$$

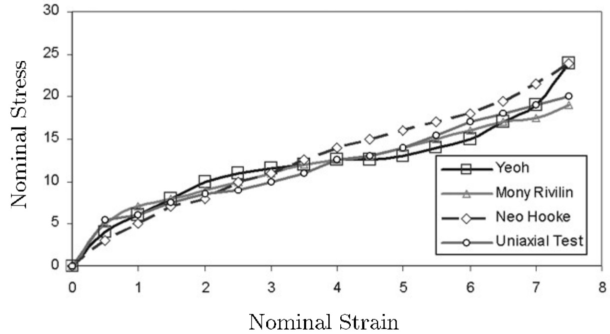

Figure 7. Comparison between the three models with the test data fit.

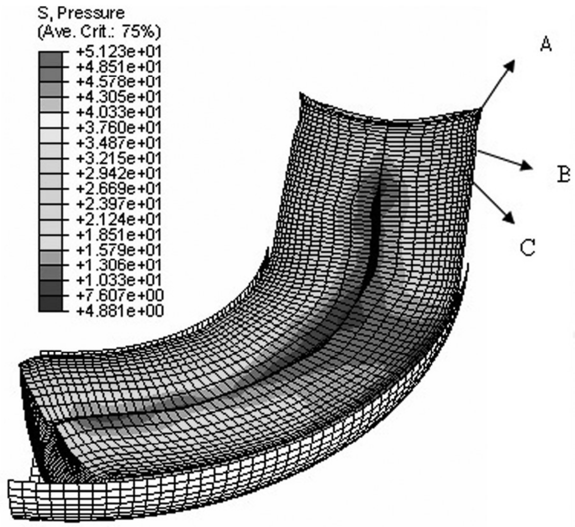

Figure 8. Pressure distribution in the soft rubber after end of analysis.

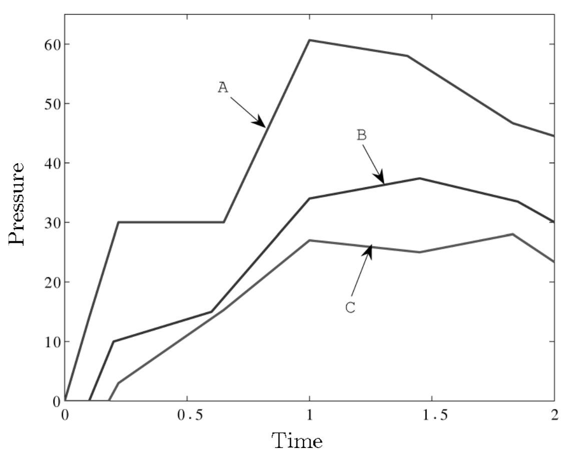

Figure 9. Pressure distribution at 3 nodes of the soft rubber (Points A, B and C see Figure 8). The points are 25mm apart.

For hard rubber, assuming elasticity module of 180 MPa, the following constants are used.

$$C_{10} = 24 \text{ MPa}$$

$$C_{01} = 6 \text{ MPa} \quad (12)$$

FEM Results of Push Bending Process

FEM simulations were performed using the tube material data of Table 1 and Mooney–Rivlin material constants given by Eq. (11) and Eq. (12) FEM results show that several types of defects such as upsetting, wrinkling, tearing and flattening can occur using either soft or hard rubber. Figures 8, 9, 10 and 11 show pressure distributions in the soft and hard rubbers during the push bending process. Figures 8 and 9 show that in the soft rubber, the hydrostatic pressure is positive every where even in the stretched zones, *i.e.* outer fibers of rubber such as A, B and C point. In other words by using a soft rubber, compressive hydrostatic stress is made in the outer region of the bend zone. This pressure remains compressive throughout the whole forming process.

However, by using a hard rubber hydrostatic, stresses at nodes A, B and C vanish at the end of the forming process, as shown in Figure 11, and it may change into tensile stress in the outer region of the bend zone, as shown in Figure 10, at point D. It means that in the stretched zones, the hard rubber is under tensile hydrostatic stress. Therefore, the hard rubber is not able to keep the tube in contact with the die. Consequently, considerable flattening occurs in the tube and there is a gap between the die and formed tube (detail B Figure 12).

Another problem encountered in the push bending process is tube upsetting in the guide zone (straight part of the tube in the feed zone). Detail C in Figure 13 shows considerable upsetting when the soft rubber is used. According to detail A in Figure 12 no upsetting is seen when a hard rubber is used. As shown in details D of Figure 13, no gap is made between the die and bent tube, due to compressive hydrostatic pressures created in the soft rubber. But detail B in Figure 12 shows that there is a gap between the tube and the die in the stretched zone when a hard rubber is used, because in the stretched zones, the hard rubber is under tensile hydrostatic stress and there is no pressure to contact the tube to the die.

If the applied axial feed exceeds a certain limit, wrinkling can also occur in the inner side of the bent tube when a soft rubber is used (Figure 14). FEM results show that wrinkling of the inner side of the tube can be prevented when a hard rubber is used (Figure 15). On the other hand tearing can happen in the outer region of bend zone, when a soft rubber is used. Tearing may occur even if a large amount of axial feed is applied. However by using hard rubber in the tube bending process no wrinkling and tearing occurs (Figure 15). Therefore, according to the above mentioned FEM results, one piece of either hard or soft rubber causes various types of defects in the bend parts.

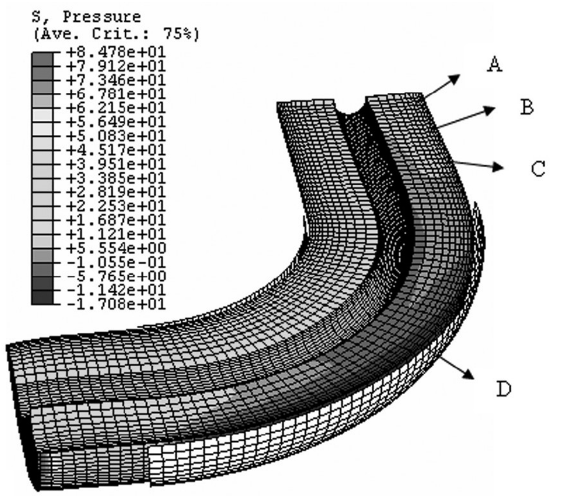

Figure 10. Pressure distribution in the hard rubber after end of analysis.

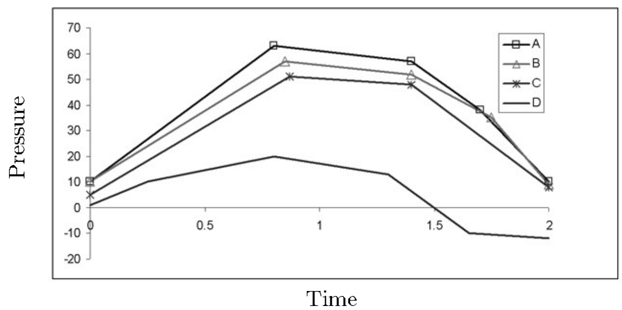

Figure 11. Pressure distribution at 3 nodes of the hard rubber (A, B and C see Figure 10). The points are 25mm apart.

Hence in order to eliminate these defects combinations of soft and hard rubbers should be used as is suggested by Armstrong *et.al.* [7]. Hard rubber (shore D) pieces are recommended to be used at the two ends of the tube and soft pieces of rubber (shore A) should be used at the middle of the tube, see Figure 16.

These FEM results are very well in agreement with Armstrong's experimental observations mentioned in the patent # 2,971,556 [6]. The main concern in Armstrong and his co- workers' arrangement of rubber pieces was longer rubber life. They didn't discuss arising defects such as flattening, upsetting and wrinkling of the bent tube. Also according to the some experimental works, they suggested that the hard rubber should be used at the two ends of the tube and the soft rubber should be used at the middle of the tube [7]. Figure 16 shows that combination of soft and hard rubbers in the push-bending process (hard rubber in the two ends of the tube and soft rubber in the middle of the tube) are helpful in eliminating bending defects. This result is in agreement with Armstrong's experimental works.

When a combination of soft and hard rubber rods are squeezed, soft rubber pieces are compressed earlier and hence will fill the tube sooner. By using hard rubber rods at the two ends of the tube, higher pressures will be built at the middle of the tube where hydrostatic stresses are actually needed in the bending process. Therefore bend quality can be improved and bending defects can be better eliminated when the above mentioned combination of rubber pieces is used.

FEM simulations show that using soft rubber in the middle of the tube eliminates flattening defect in the outer region of the tube *i.e.* where the tube is under tension (Figure 16, detail G) and using hard rubber at the two ends of the tube can eliminate upsetting and wrinkling of the bent tube (Figure 16, details H,I).

CONCLUSIONS

1. Pressure distributions inside the rubber can be estimated using either a simple closed form equation or the FEM method.
2. Various types of defects encountered during push bending process can be predicted by FEM simulations.

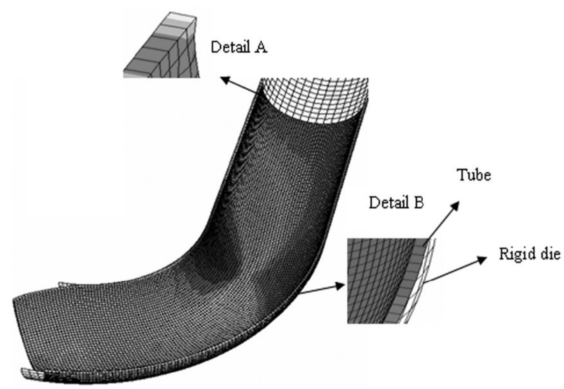

Figure 12. Stress distribution in the longitudinal direction of the tube after the bending process using hard rubber.

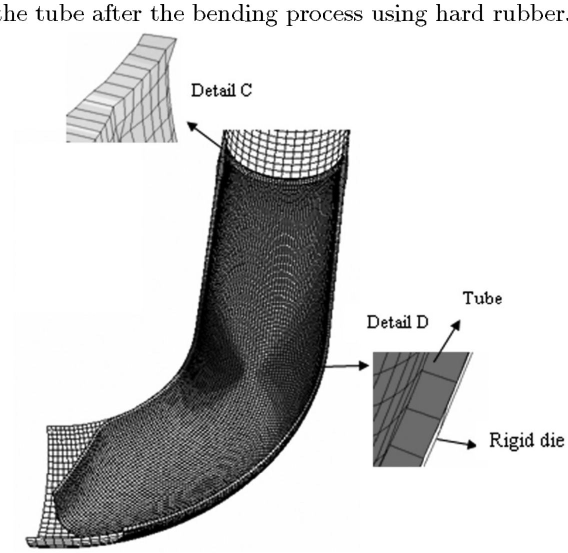

Figure 13. Stress distribution in the longitudinal direction of the tube after the bending process using soft rubber.

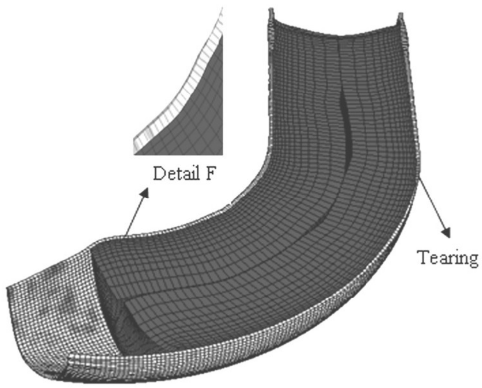

Figure 14. Wrinkling occurs when a soft rubber is used, (Detail F).

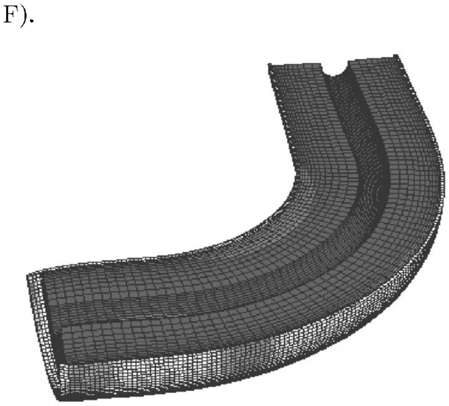

Figure 15. No wrinkling is seen when a hard rubber is used.

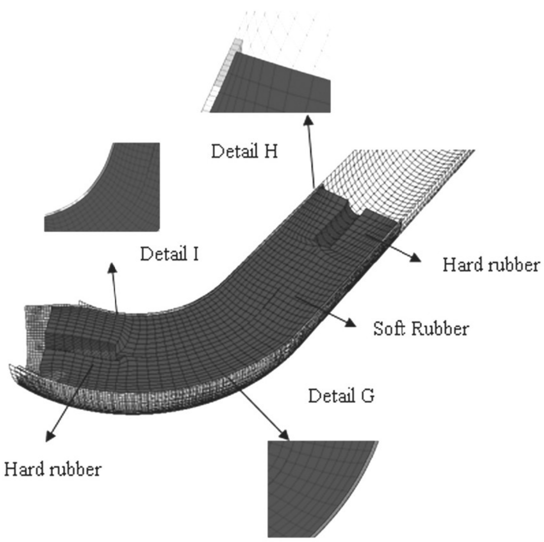

Figure 16. Combination of soft and hard rubbers in the push-bending process is helpful in eliminating bending defects.

3. FEM results show that using soft rubber pieces in the middle of the tube keeps it in contact with the die during the whole bending process. Hence no flattening occurs in the outer region of the tube *i.e.* where the tube is under tension. According to these FEM results the end of the tube which is pushed through the die can undergo an upsetting process while the other end may suffer a wrinkling defect.
4. Using only hard rubber pieces in the tube can not keep the tube in contact with the die and hence an oval tube section will be made. However upsetting of the feed end and wrinkling of the back end will be eliminated.
5. In order to prevent all possible defects, a combination of soft and hard rubber pieces is recommended. For this purpose hard rubber pieces are to be used at the two ends of the tube and soft rubber should be used in the middle of the tube.
6. When a combination of soft and hard rubber rods are squeezed, soft rubber pieces are compressed earlier and hence will fill the tube sooner. By using hard rubber rods at the two ends of the tube, higher pressures will be built at the middle of the tube where hydrostatic stresses are actually needed in the bending process. Therefore, bend quality can be improved and bending defects can better be eliminated when the above mentioned combination of rubber pieces is used.

REFERENCES

1. Yang H., Lin Y., "analysis for Forming Limit of Tube Bending Processes", *J. Mater. Process. Tech.*, **152**, PP 363-369(2004).
2. Zeng Y., Li Z., "Experimental Research on the Tube Push-Bending Process", *J. Mater. Process. Tech.*, **122**, PP 237-240(2002).
3. Wang X., Cao J., "Wrinkling Limit in Tube Bending", *Trans. ASME*, **123**, PP 430-435(2001).
4. Yang H., Lin Y., Zhichao S., "Advanced Plastic Processing Technology and Research Progress on Tube Forming", *J. Plasticity Eng.*, **8(2)**, PP 86-88(2001).
5. Yang J., Jeon B., "The Tube Bending Technology of a Hydroforming Process for an Automotive Part", *J. Mater. Process. Tech.*, **111**, PP 175-181(2001).
6. Trana K., "Finite Element Simulation of the Hydro Forming Process-Bending, Performing and Hydro-Forming", *J. Mater. Process. Tech.*, **127**, PP 401-408(2002).
7. Armstrong D.E., et al., "Cold Tube Bending and Sizing", *UNITED STATES PATENT*, PP 971,556(1961).
8. Baudin S., Ray P., Mac Donald B.J., Hashmi M.S.J., "Development of a Novel Method of Tube Bending Using Finite Element Simulation", *J. Mater. Process. Tech.*, PP 153-154(2004).
9. Gent A. N., *Engineering with Rubber-How to Design Rubber Components*, (1992).
10. Karlesson H., Sorensen, *Abaqus user manual*, (2001).
11. ASTM, *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers Tension*, D412-98a, (1998).