A ROTARY DRAW BENDING OF RECTANGULAR TUBES: EXPERIMENTS AND NUMERICAL ANALYSES

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ABSTRACT

This paper is aimed at investigating the rotary draw bending of rectangular tubes. For this purpose, tubes with rectangular cross section of 20x40 mm, thickness 1.5mm, made of steel Fe430 were bent, both the “hard way” and the “easy way”, to form a nominal angle of 90°. A Finite Element (FE) model was developed to perform the process simulation based on an explicit dynamic time integration scheme using the commercial code ABAQUS. The FE outcomes have been validated by comparison with experimental results. Specifically, a Coordinate Measuring Machine (CMM) was used to determine the degree of bend as well as the radius, the profile and the wall thickness of the bent sections. The obtained results showed the capability of the FE modelling to predict the material deformation process.

Keywords: draw bending, tube, FEM, elastic mandrel, thickness

INTRODUCTION

Rotary draw bending of tubes is a very important production method adopted in different industrial branches, such as automobile, aircraft, air conditioner, gas plans, fluid lines, etc. In the majority of applications, round tubes are bent because the axisymmetry of the part helps reduce any type of distortion. However, some structural applications, like roll-over protection, frameworks, bumpers, playground equipment, require to bend rectangular tubes. This is not an easy task, in fact the bending of rectangular tubing can result in distortion, the most common of which is concavity on the inside diameter of the section. Tube bending can be performed by different techniques such as tube compression, press bending, roll bending, etc. [Vollertsen, 1999] [Yang, 2012]. Rotary draw bending will be considered in this work because it particularly suitable for thin-walled tubes. Such manufacturing process is not simple to investigate through analytical models or experiments because it includes material and geometries nonlinearity; hence, the rectangular shape of tubes adds more complexity to the problem.

The operating components used in the process are: bend die, clamp die, pressure die, wiper die and mandrel; the last one is a component having adaptive form, which prevents the tube section from distortion and collapse due to buckling. In the usual bending of round tubes, the mandrel consists of a fixed part connected to a row of rounded rigid metal blocks jointed each other [Xue, 2015]. Usually, the same mandrel can be conveniently shaped to fit to rectangular pipes, but recent developments suggest substituting it with an internal mandrel of high-density-plastic, pressed against the bent sections.

Elastic spring back needs to be compensated by overbending the tube, but the extent of the angular displacement to apply to the workpiece is not known a priori. Therefore, the setting of
the process parameters is usually tackled and partially solved by *trial-and-error* approaches based on expensive experimental campaigns [Zhu, 2013]. In order to efficiently predict the process outcome, numerical analyses based on finite elements (FE) simulations can be very effective. [He, 2009] [Heng, 2007] [Jafari, 2013]. However, FE simulations are highly nonlinear and strongly dependent on the time variable. Under these conditions, a critical issue of the simulation is represented by the computational heaviness, since, if compared with conventional processes, the modeling of tools paths is very time expensive and requires a very hard dynamic analysis. For this purpose, a move towards the use of dynamic explicit time integration schemes has appeared to be promising in the literature [Zhao, 2009], as, owing to the strong nonlinear events occurring during the process, the implicit methods often fail to converge.

In the present paper, a numerical and experimental approach has been adopted, based on the development of a finite element model able to simulate the entire tools trajectory during the forming process. The computational model has been implemented and validated by a specific experimental investigation covering the production of sample geometry on a workbench specifically developed.

In particular, tubes made of steel Fe430 with rectangular section of 20x40 mm (see Fig.1a) and thickness 1.5 mm were bent both the “easy way” or EW (about the x-x axis) and the “hard way” or HW (about y-y axis), in order to study the different tube bending resistance in relation to the bending-direction.

![Tube Cross-Section](image)

Fig. 1 - Cross-Section of rectangular tube: (a) Nominal dimensions in mm; (b) wall-names

The FE outcomes have been validated by comparison with experimental results. Specifically, a Coordinate Measuring Machine (CMM) was used to determine the degree of bend as well as the radius, the profile and the wall thickness of the bent sections. The obtained results showed the capability of the FE modelling to predict the material deformation process.
EXPERIMENTAL MATERIAL

Rolling forming and welding manufacture is the process adopted to obtain the specimen-tubes.

Taking in account the usual denominations, the four walls of rectangular pipe are named inner flange IFG, outer flange OFG, right web RWB and left web LWB (see Fig 1b); The first and the second one are the closest and the furthest wall to bending axis, respectively. The remaining two, perpendicular to the same axis, work as lateral supports for the section.

The tube is made of construction steel Fe430, whose monotonic tensile proprieties were determined in [Benedetti, 2015] and are displayed in Table 1. The alloy is assumed isotropic for simplicity, implementing elastic and plastic behaviours.

<table>
<thead>
<tr>
<th>Fe430 Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Kg/m³</td>
<td>7800</td>
</tr>
<tr>
<td>Young modulus</td>
<td>GPa</td>
<td>206</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Yield stress</td>
<td>MPa</td>
<td>330</td>
</tr>
</tbody>
</table>

As shown in Fig. 3, the welding seam is located along the centre line of the tube web.

The influence of the weld joint on the local mechanical properties of the tube is evaluated by means of microhardness measurement. Specifically, the cross-weld hardness profile is obtained using a Vickers microhardness tester. An indentation load of 500 g and a time-dwell of 10 s are used. The indentations are spaced 0.2 mm apart, covering base material (BM), heat affected zone (HAZ) and weld metal (WM). Fig. 4 illustrates the microhardness dependence
upon the distance from the weld centre. It can be noted that the fusion material displays a microhardness significantly higher than the parent metal, ranging between 280 HV$_{0.5}$ in WM and 160 HV$_{0.5}$ in the BM. The microhardness markedly increases in the HAZ, i.e. a transition region of about 2 mm width comprised between BM and WM. Apparently, WM and HAZ are hardened due to cooling after welding.

EXPERIMENTAL PROCEDURES

The functional layout of the CNC machine used for the rotary draw bending tests is shown in Fig. 5.

The "pressure die" or "Travelling pressure die" (PD) is always in contact with the tube's outer wall (OFG) without any normal relative motion. It helps reduce galling and marking of the tube by alleviating the drag occurring during bending and wall thinning on the external wall. Sometimes the rear side of tube is sustained by a rear “booster” in order to control the linear sliding. For simplicity, this latter component will be not considered in the present work. The
"Clamp Die" clamps the tube against the "Bending die" (BD). The last one rotates about its principal rotation axis drawing the tube with it. In this study, the BD’s groove, having radial rectangular section, is designed for the specific tube’s section and the required bending direction (EW or HW). The mean radius determines the final middle curvature of the tube.

The “wiper” is usually made up of a low friction alloy, for instance bronze; it reduces the wrinkling phenomenon and distortions of tube’s IFG before getting in contact with the bending die. Wrinkling, caused by several operating conditions (material anisotropy, wiper position, clearance mandrel-tube, etc.), is one of the main issues in tube bending and is currently thoroughly investigated by several researchers [Kourosh, 2013] [Gangyao Zhao, 2010].

One of the most promising ways to reduce wrinkling and distortions is the adoption of a “Mandrel” that averts the flattening at the outer wall OFG [Jun Fang, 2013]. This component, placed inside the tube, operates like a core, which, during the working process, “supports” the sliding tube’s walls and avoids their relative collapse. It is common practice to avoid its use when the bending die radius is small because of excessive thinning of the walls at the stretched zone.

The rotary draw bending tests were performed by imposing to the linear and rotary actuators the paths illustrated in Fig. 6a and 6b, for EW and HW bending, respectively. Specifically, the BD tool rotates by an angle 90° and 93°, in HW and EW, respectively. Usually, overbending is applied to compensate the springback so as to reach the target bending angle. The bending radius is 98 mm and 74 mm for HW and EW, respectively.

![Fig. 6 - Angular/linear position v.s Time of BD and PD for EW Bending with “overbending” (a) and HW Bending (b);](image)

The final shape of the tubes after forming is evaluated using a Coordinate Measuring Machine (CMM). For this purpose, the outer and the inner surface were scanned along paths at different distances $h_{sec}$ from the lateral surface of the tube, as schematically shown in Fig. 7.

Moreover, CMM is used to scan the external perimeter of tube cross-sections located at different angular positions $\alpha_{sec}$ (Fig. 7) and to measure the thickness of the outer and inner walls after sectioning the tubes along the midplane.
THE FINITE ELEMENT MODEL

The FE Model, shown in Fig. 8, is developed in Abaqus CAE environment and represents a conceptual simplification of the draw-bending machine components involved in the process.

The very small ratio between the thickness and the other dimensions of the tube suggests using shell elements, even though the use of brick elements could account for the not negligible transversal shear deformation in the material during the drawing process.

The use of brick element introduces however some problems concerning the very unfavourable element aspect ratio and produces a significant increment of the computational heaviess of the analysis, being the time step strictly influenced by the smallest element dimension. Shell elements were therefore adopted in the present case for building up the model.

The tube was discretized using 4-nodes shell element (S4R) that enforces a Mindlin-Reissner type of flexural theory, characterised by reduced integration scheme, hence suitable for large deformation large-strain [ABAQUS, 2012]. Instead, the cylindrical support, the pressure die and the clamp die are meshed with linear brick 8-nodes elements (C3D8R). The mesh has been refined after a convergence analysis. The optimal element size has been found to be about 5x1 mm, the longest side is parallel to the tube principal axis. The contribution of the fillet at the junctions between the tube walls is neglected; hence the tube section is modeled with sharp edges. Initially, the tube material has been assumed to be homogeneous, thus
neglecting the presence of the weld seam. This issue will be addressed at the end of the paper. The tube characteristic dimensions used in the model slightly differ from the nominal ones and have been measured with caliper and CMM.

To model the kinematics of the machining tools, rigid-body-constrain with infinite stiffness are imposed to the cylindrical support, which works as an axial prismatic joint on the tube, the clamp die, the bending die, the pressure die, and the wiper. This seems reasonable in view of the much higher compliance of the tube and the conspicuous reduction in computational cost. The wiper is modeled as an ideal undeformable shell.

![FEM model in ABAQUS](image)

The "Mandrel", made of extruded polyamide 6, is a parallelepiped with chamfered terminal section. It is fixed and constrained inside the tube with a clearance of about 0.25 mm. In the numerical analysis, it is meshed with the brick elements C3D8R. The material is assumed completely linear elastic, because the relative deformations are not enough to produce plastic strains. The mechanical properties are taken as those declared by the supplier company.

The relative position of the mandrel with respect to the bending die is shown in Fig. 9. Accordingly, $X_{mdt}$ is distance between mandrel’s tip and bending die’s axis, projected along principal tube’s axis the mandrel. This parameter specifies how much the component protrudes with respect to the zero position ($X_{mdt} = 0$), which corresponds to the tangent to the cylindrical surface of BD. During EW bending, the mandrel is positioned at a distance $X_{mdt} = 30$ mm, while; in the HW process $X_{mdt}$ is set to 0 because that configuration shows more structural stiffness respect to the previous one, therefore the thin walls shall not collapse.
RESULTS FOR EASY WAY BENDING

In fig. 11a and 11b, the numerical and experimental profiles of OFG and IFG for EW bending are plotted on different section planes normal to BD’s rotational axis. The position of section plane is defined by \( h_{sec} \), as shown in Fig. 7.

As index of the accuracy of the numerical results in representing the actual tube shape, we have evaluated the Root-Mean-Square (RMS) of the deviation of FEM results with respect to experimental data; the outcomes are shown in Table 2.

<table>
<thead>
<tr>
<th>( h_{sec} ) [mm]</th>
<th>RMS dev. [mm]</th>
<th>Mean Err. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.5045</td>
<td>0.4397</td>
</tr>
<tr>
<td>20</td>
<td>0.6297</td>
<td>0.5175</td>
</tr>
</tbody>
</table>

Fig. 11 - Tube Profile in EW Bending, section plane defined in (a) \( h_{sec} = 10 \) mm and (b) \( h_{sec} = 20 \) mm;
Moreover, numerical and experimental estimations of the cross-section profiles taken at different angular position are compared in Figures 12a, 12b and 12c, showing a good agreement.

Fig. 12 - EW Bending results: Tube Cross-Section in (a) $\alpha_{sec} = 114^\circ$, (b) $\alpha_{sec} = 140^\circ$ and (b) $\alpha_{sec} = 160^\circ$; Thickness Profile on section plane $h_{sec} = 14 \text{ mm}$

Figure 12d shows the comparison between the numerical and experimental evaluation of the IFG and OFG wall thickness scanned as a function of the angular position $\alpha_{sec}$. As expected, the outer surface experience a wall thinning that may affect its mechanical resistance.

RESULTS FOR HARD WAY BENDING

In this paragraph the outcomes of the analysis of the HW Bending are presented following the same procedures, concepts and references of the previous one. The profiles present great deviations from the experimental points in comparison with the previous one, as shown in Table 3 and Fig. 13.

<table>
<thead>
<tr>
<th>$h_{rez}$ [mm]</th>
<th>RMS dev. [mm]</th>
<th>Mean Err. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.485</td>
<td>1.468</td>
</tr>
<tr>
<td>9</td>
<td>1.126</td>
<td>1.014</td>
</tr>
</tbody>
</table>
Instead, thickness is correctly evaluated and it follows the same trend. This unsatisfactory agreement is imputed to the presence of the weld joint on the inner surface. In fact, the higher hardness of HAZ and WM suggests that the inner surface hinders the plastic flow involved in the metal forming in a greater extent than that modeled in numerical analyses. This issue will be addressed in the following Section.

Fig. 13 – HW Bending without welded material assumption; Profiles on section plane defined in (a) $h_{sec} = 5\ mm$ and (b) $h_{sec} = 9\ mm$; Tube Cross-Section in (c) $\alpha_{sec} = 114°$, (d) $\alpha_{sec} = 140°$ and (e) $\alpha_{sec} = 160°$; (f) Thickness Profile on section plane $h_{sec} = 8\ mm$
EFFECT OF THE WELD JOINT

The results of the microhardness tests have been used to reconstruct the mechanical properties of the weld joint to be implemented in the FE simulations. Since the yield stress $\sigma_y$ is nearly proportional to the hardness $HV$, the following equation is used to estimate the yield stress of the weld metal $\sigma_{yw}$:

$$\sigma_y \propto HV$$

$$\sigma_{yw} = \frac{HV_w}{HV_i} \cdot \sigma_{yi}$$

where:

- $HV_w$ is the hardness of weld metal;
- $HV_i$ and $\sigma_{yi}$ are, respectively, original hardness and yield stress of the base material (BM);

The monotonic tensile curve of the weld material is obtained by increasing the elastic regime up to the local yield stress value $\sigma_{yw}$ and appropriately shifting the hardening curve in order to compensate the offset due to the residual deformation, as shown in Fig. 14.

For the sake of simplicity, the weld joint is divided into a weld metal (WM) zone and heat affected zone (HAZ), as shown in Fig. 15, where the hardness is indicated as $HV_{WM}$ and $HV_{HAZ}$, respectively; the predicted yielding stresses are respectively $\sigma_{yw}^{WM}$ and $\sigma_{yw}^{HAZ}$. See Table 4.

<table>
<thead>
<tr>
<th>Location</th>
<th>Young Module [N/mm²]</th>
<th>HV average [HV]</th>
<th>$\sigma_y$ [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM</td>
<td>206000</td>
<td>282.79</td>
<td>606.2527</td>
</tr>
<tr>
<td>HAZ</td>
<td>206000</td>
<td>244.7246</td>
<td>524.6471</td>
</tr>
<tr>
<td>Base Material</td>
<td>206000</td>
<td>153.7833</td>
<td>329.6845</td>
</tr>
</tbody>
</table>

Fig. 14 – Curve stress-strain, “shifting” due to welding.
The mechanical properties of the three regions of the weld joint are implemented in the FE model.

![Welding seam in ABAQUS](image)

Fig. 15 - Welding joint is divided in three regions in the FE model

Table 5 and Figures 16a and 16b demonstrates that accounting for the local mechanical properties of the weld joints permits to improve the accuracy of the estimation of the tube profile and cross-section.

<table>
<thead>
<tr>
<th>$h_{sec}$ [mm]</th>
<th>RMS dev. [mm]</th>
<th>Mean Err. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.725</td>
<td>0.699</td>
</tr>
<tr>
<td>9</td>
<td>0.795</td>
<td>0.755</td>
</tr>
</tbody>
</table>

![Graphs](image)

Fig. 16 — HW Bending, assuming welding seam; (a) Profiles on section plane defined in $h_{sec} = 9$ mm; (b) Tube Cross-Section in $\alpha_{sec} = 140^\circ$

**CONCLUSIONS**

A Finite Element simulation of rotary draw bending of rectangular tubes has been developed and validated. The tubes were obtained through rolling forming and welding of steel sheets. We found that the mechanical properties of the weld joint significantly affects the forming process, especially if the weld joint is located on the inner surface of the bent tube. In the next
future we propose to investigate the effect of other process parameters, such as the position of the mandrel, the clearance tube-mandrel and tube-wiper, bending radius, material anisotropy and friction coefficient.

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