Sensitivity analysis of process and tube parameters in free-bending processes

N Beulich¹, J Spoerer¹ and W Volk²

¹Product, Process Planning Special Technologies, BMW Group, 84122 Dingolfing, Germany
²Chair of Metal Forming and Casting, Technical University of Munich, 85748 Garching, Germany

E-mail: nikolas.ba.beulich@bmw.de

Abstract. Free-bending processes are used to manufacture highly-complex profile shapes for different kinds of industry sectors. This paper focuses on the enhanced version of the MOS bending technique (6DOF), which is used by BMW to produce semi-finished products for the tube hydroforming process. In order to achieve a better process understanding, the bending process was analyzed with regard to process and tube parameters. In the first experimental bending series, the process precision was measured and evaluated by standard deviation and process capability. In the second bending series, the analysis focuses on the weld seam position and the wrinkling behavior of the tube. The correlations shown between process parameters and the resulting bending geometry are the basis for the validation of a process simulation model developed in LS-Dyna. Therefore, the comparison of experimental data and data measured numerically represents a good agreement. The FEM model was used to perform a numerical based sensitivity analysis of the bending process in relation to process and tube parameters. The result identifies the main factors contributing to the free-bending process.

1. Introduction

The MOS bending technique is used to produce three-dimensional bent tubes as the preforming step in the hydroforming process chain. Increasing the part complexity and the application of innovative materials means that a robust process design and control is required. Knowledge about the main contributing factors to process stability is a big advantage, in particular during the dimensioning and operation of the bending process. For this reason, this paper will study the influence of process parameters on the MOS-bending technique with 6 DOF. This overall technology was developed by Murata, Uemura et al. [1] and enhanced by the company J.Neu [2] from 3 DOF to 6 DOF. Figure 1 shows the bending principle of the MOS bending technique. To produce a bent profile, the tube is pushed through the fixed guide at the tube end with a constant velocity along the x-axis. During tube movement, the bending die is positioned in the y-z plane to realize a desired tube curvature and torsion. In addition to the possible deflections along the y and z coordinate, the die is also able to rotate about the x, y and z-axis. The offset from guide to die (kval) is fixed. Ganter analyzed MOS bending with 3DOF and measured a maximum process deviation for aluminum tubes of around 11 mm/m bending length, and also specified important factors that influence free bending technologies. These include friction conditions, tube properties, precision of tool positioning and stiffness of the bending machine. [3] Guo, Xiong et al. have gone one step further and performed a sensitivity analysis to predict the kinematic process behavior by a change of aluminum alloy from 1100 to 6061-T6 [4].
In addition to the MOS bending technique, Kersten drafted the main factors influencing the three-roll push bending process [5] and Engel, Kersten analyzed the influence of spring-back, tool position, machine stiffness and tube properties on the bending result [6]. Vatter performed an extensive study on the same bending technique in relation to the tube curvature and torsion. As well as an experimental bending series, Vatter, Plettke performed a numerical process study with regard to geometrical tube properties [7], Merklein, Vatter et al. performed a study on tube material influences [8] and different process parameters. [9] FEM simulation models for the MOS bending technique had already been developed by Murata, Mochizuki [10], Gantner, Bauer et al. [11], Guo, Xiong et al. [12] and Beulich, Craighero et al. [13, 14]. The upcoming chapters provide an overview of the different process influence factors, the results of a bending series performed with regard to process deviation, the comparison between FEM simulation and experimental observations and the sensitivity analysis of process parameters on the free bending technology.

2. Process influence factors

In Figure 2, the factors influencing MOS bending technique are drafted and rated in terms of their effect on the bending result. Therefore, the information from literature research was analyzed and assigned to the MOS bending with 6 DOF. The stiffness and tool control of the 6 DOF bending machine, in particular, was highly improved in relation to older machine setups, which leads this to be categorized as a weak influence on the bending process.

3. Process deviation and capability

To determine the process deviation, tubes were bent to a three-dimensional part shown in Figure 3. The profile is a combination of 4 bends with different radii and bending directions and is close to a part in series production with a total length of 2,650 mm.
The tubes used for the bending series are manufactured from a coil by means of a roll-forming process and welded longitudinally using the high-frequency method. The material used is an EN AW-5182 aluminum alloy. The tube dimensions for three different batches C1, C3, C4 plotted in Figure 4, show a high inhomogeneity with regard to the diameter, as well to the sheet thickness (measured by a coordinate measuring machine – Zeiss Prismo 7 S-ACC VAST). The mean values of diameter and thickness are shown in the figure legend.

The process deviation was calculated from the bending line of 26 tubes from the batch C4. Therefore, the tube surface was measured in Polyworks IMInspect2017 with a HEXAGON ROMER Absolute Arm. Afterwards, the bending line was reconstructed by means of iterative cylinder fitting through the measured tube surface. To calculate the deviation between the single bends, the bending line was oriented as follows: 1. The origin of the bending line is located at the start position (Figure 3) and the local x-axis points tangentially along curve. 2. The z axis is fixed at the tube end position. 3. After the coordinate transformation to global Cartesian coordinates, the bending line was interpolated equidistant. The measurement of standard deviation (shown in Figure 5) is performed along the bending line from start to endpoint. It shows that the deviation increases with increasing distance from the orientation point. Therefore, the development of the course is nearly linear and can be expressed as a deviation of 9.2 mm per 2,650 mm of bending line (or 3.54 mm/m bending line). With regard to the process capability indices, it is now possible to calculate the necessary specification limits for subsequent forming or joining operations.

\[
C_p = \frac{USL - LSL}{6\sigma}^{-1}
\]  

In the hydroforming process chain, the bending operation is followed by a preforming operation. Because of the request for a stable process chain, the process capability index \(C_p\) \((1)\) [15] has to be greater than two. With the tube profile considered symmetric from the middle of the bending line (shown in Figure 3), the maximum distance in both directions is 1,325 mm. Therefore, the standard deviation is calculated by \(\sigma = 1.325 \text{ m} \times 3.54 \text{ mm/m} = 4.64 \text{ mm}\). The minimum total specification limit at the end of the tube has to be at least \((USL-LSL) = 55.68 \text{ mm}\) (calculated by \((1))\). These bounds results in a preforming tool with movable segments to meet the demands of the bending deviation.

![Figure 3. Bending profile used in experiments.](image)

![Figure 4. Measured geometry of welded, high precision EN AW-5182 tubes.](image)
4. FEM simulation model for the MOS bending method

To gain a more detailed understanding of process influence factors, a simulation model is built to perform numerical based parameter studies. The simulation model is built in LS-Dyna according to the specifications in [14]. The main settings are taken from the forming guidelines by Maker and Zhu [16]. LS-Dyna specific keywords and theory basics are described and explained in [17–19]. The tools (mandrel, guide, die) are modeled as rigid shells with Belytschko-Tsay elements without thickness consideration. The tube is also meshed with Belytschko-Tsay elements with 4 mm edge length and 5 trough thickness integration points. The stress and strain distribution from the roll-forming process was simulated and mapped to the closed tube mesh before the start of bending simulation. During the bending process, the tube is pushed with a 10-fold increase in pushing velocity. The solver version used is the R9.3.0 in single precision with 72 cores in MPP mode. Because of the explicit solving algorithm, selective mass scaling was used with a total mass increase of about 20%. This results in a total calculation time of about 7.5 hours. Standard penalty-forming contacts were used for all contact zones. The coefficients of friction are 0.08 for the contact between guide/tube and die/tube and 0.15 for mandrel/tube. The elastic-plastic properties of the tube are expressed by the Barlat YLD-2000 yield function and the isotropic-kinematic hardening was approximated by the model of Chaboche-Rousselier. The weld line strength of the tube (e.g., increased yield strength) is constituted by a hardness increase during roll-forming simulation in the area of the strip edges and also mapped on the tube mesh. The definition of the weld line thickness differs from the overall sheet thickness (Figure 4 border of thickness distribution) with an increase to 2.3 mm. Therefore, a single element row was selected along the weld line, and a new thickness was defined for this area. The influence of weld seam position on the bending result and tube wrinkling tendency was analyzed in order to provide an overview of the precision of the simulation model.

Figure 5. Standard deviation and density function of bending experiment.

Figure 6. Strong wrinkling at radius 1.

Figure 7. Weak wrinkling at radius 4.

Figure 8. Decrease of wrinkling by decrease of lubricant (a to c).
5. Correlation analysis

During the bending tests performed on 26 tubes of batch C4, wrinkling was observed in 10 of 26 tubes. Thereby different strong wrinkling occurred on the profiles only in radius 1 and 4 (mainly wrinkling in radius 1 (Figure 6), weak or no wrinkling in radius 4 (Figure 7)). When the same profile was bent with tubes of batch C1 and C3 (10 tubes each), no wrinkling was observed. By analyzing the mechanical tube properties, the tube surface roughness and the tube homogeneity (hardness distribution) no suspicious difference was observed. The only measurable deviation between batch C4 and C1, C3 was a change in the mean diameter from 64.03 mm to 64.075 mm (Figure 4). Adopting the geometrical tube dimensions for the simulation model resulted in a precise representation of wrinkling tendency in the first radius. Figure 9 shows the simulation result in terms of the maximum effective plastic strain (EPS). This leads to the conclusion that the tube dimensions have a significant influence on wrinkling behavior during the free-bending process. Figure 8 shows the influence of the amount of lubrication on the wrinkling occurrence for the same bending profile. It follows, therefore, that friction behavior also has a strong relation to wrinkling occurrence. With the assumption that a higher amount of lubricant results in a lower friction coefficient, the simulation model shows strong wrinkling for friction coefficients around 0.10, medium wrinkling around 0.16 and no wrinkling starting from 0.18. The distribution of the friction coefficient on the different tool couples also results in different wrinkling behavior.

In addition to the wrinkling tendency analysis, another bending series was performed to show the effect of weld seam position on the bending result. For this, a series of a single, two-dimensional bends was performed with a variation of weld seam position from 0° to 180° (0° describes the weld seam position at the inner side of the bend, directly in the bending plane). The bending result (experimental and simulative) was evaluated in terms of bending angle and bending radius. A robust method of radius
measurement was developed and is shown in Figure 10. Once the bending line had been reconstructed, the bending plane was transformed in the global Cartesian x-y plane. To determine the exact center point of the radius on the bending line, an optimal bend was fitted to the bending line by means of nonlinear optimization (least-square distance). The bending angle was measured using the straight lines at the start and end of the fitting profile. For the radius measurement, a group of points around the determined center of the bend was used to perform a circle regression on the bending line raw data. It is necessary to get a minimum number of points (in respect to the measurement interval) in the bending area with constant curvature, as plotted in Figure 10, in order to receive a robust radius measurement using the regression method. The regression method minimizes the orthogonal distances from raw data to fitted circle by using the Levenberg-Marquardt scheme in Matlab R2018b [20]. To see the weld seam influence on the bending result, the measured angles and radii are plotted in Figure 11. This shows that a weld line position at the inner bend leads to a higher bending angle. When the weld line moves to the outer bend, the bending angle decreases. The simulation results, with the weld seam properties explained above, show a strong correlation with the experimental results.

6. Sensitivity analysis

Once the simulation model performance has been demonstrated, a numerical based sensitivity analysis is performed to gain information about the influence of the parameters shown above on the tube wrinkling behavior and the bending result in terms of bending angle and bending radius. Therefore, the simulation model in LS-Dyna was integrated in the optimization tool LS-Opt to perform a Design of Experiments (DOE) analysis. For each design point, the run starts with the initialization of the tube mesh, followed by the bending simulation and a spring-back operation. Afterwards, multiple post processing scripts generate the tube centerline and extract bending strain and bending force data. In the DOE, the following parameters were varied: diameter (63.85-64.15 mm), sheet thickness (1.9-2.1 mm), coefficient of friction (COF) guide/die/mandrel (0.08-0.18), mandrel position (-12 – 0 mm in relation to guide position), weld line thickness (2.1-2.35 mm), weld line position (0°-180°) and scale factor for the yield curve (0.85-1.15). The statistical experimental design includes 400 sampling points, distributed by a space-filling algorithm [21]. The kinematic profile of the bending test and the tool geometry was constant during the analysis. The DOE was analyzed in relation to the wrinkling behavior of the process. The selected result variable is the maximum effective plastic strain at the inner bend of the tube. Figure 12a shows the plotted result of the analysis of variance (ANOVA) in terms of input parameters and EPS inner. Here, the tube dimension (diameter and thickness) shows the highest sensitivity in terms of the EPS inner. This matches the observation made during the bending experiments described above in this paper, in which the wrinkling was caused by a change in tube diameter. In the scatter plot shown in
Figure 12b, the diameter and the thickness are plotted over the EPS inner. It is clear that the data points are split into two result levels. The experiments with EPS below 0.4 have no wrinkle occurrence, whereas all points with EPS above 0.4 have wrinkles in the inner bend. When we observe the diameter-to-thickness relation of the tube, we can see that experiments with a big diameter and a small thickness (big diameter of neutral layer) have no wrinkles. Conversely, tubes with a small diameter in the neutral layer show wrinkling in the bending result.

When the DOE is analyzed with regarding to the bending result in terms of bending angle and bending radius, the main contributing factors can be named as the mandrel position, tube diameter and COF of the die (Figure 13).

To improve the performance of the MOS bending technology and reduce the measured process deviation, the following changes need to be made:

- Modify design of bending profile and tools, so that no wrinkling can occur by variation of tube dimension within the production tolerances.
- Increase precision of tube lubrication inside and outside of the tube to reduce process deviations.
- Increase precision of tube dimension to reduce process deviations.
- Develop tools, that allow an adjustment of the contact gap between tools and tube to adapt their position regarding to tube dimensions.
7. Summary and further research

This paper describes the different influence factors on the MOS bending technique. It therefore provided an overview of all possible parameters, and the parameters were weighted by their influence. In the first bending series, the process deviation for a close-to-production bending part was measured by evaluating the tube bending lines. This resulted in a standard deviation of 3.54 mm/m bending length. With this data, the process capability and the tolerance limits of subsequent forming operations can be calculated in advance to ensure a stable production process. The simulation model build in LS-Dyna showed a strong correlation between the wrinkling tendency of the bend tubes and the positioning of the weld seam. By evaluating the bending results, we could also provide a robust method of determining bending angle and bending radius.

After conducting a DOE analysis of process parameters, it was clear that the tube dimensions have the highest influence on tube wrinkling failure. A ranking of process variables in terms of their influence on bending angle and radius was also created. This allowed us to determine how to improve the bending process quality and reduce the process deviation.

To expand the application of the bending technique, we considered a control loop, which should adapt the kinematic control in terms of tube dimensions. Also the lubrication of the tube should be monitored during production process to reduce process deviations.

Future plans have been set to design the bending process and define the bending tools with respect to the tube tolerances in order to prevent wrinkling failure when tube batches are changed.

References

[1] Murata M, Uemura Y and Suzuki H 1990 advanced Technology of Plasticity 1573–8
[2] Kuhn D 2012 MM Maschinenmarkt - Das Industrie Portal
[3] Gantner P 2008 The Characterisation of the Free-Bending Technique (Glasgow: Caledonian University)
[4] Guo X, Xiong H, Xu Y, El-Aty A A, Ma Y, Zhao Y and Zhang S 2018 Int J Adv Manuf Technol 84 363
[5] Kersten S 2013 Prozessmodelle zum Drei-Rollen-Schubbiegen von Rohrprofilen: (eng. processmodels for the three-roll-pushbending of tubeprofiles)
[6] Engel B and Kersten S 2010 30. EFB-Kolloquium Blechverarbeitung
[7] Vatter P and Plettke R 2013 Advanced Materials Research 769 181–8
[8] Merklein M, Vatter P, Plettke R and Grüner M 2012 Werkstattstechnik online 10
[9] Vatter P 2014 Sensitivitätsanalyse des 3-Rollen-Schubbiegens auf Basis der Finite Elemente Methode: (eng. sensitivity analysis of the tree-roll-pushbending by fem analysis) (Bamberg: Meisenbach Verlag)
[10] Murata M and Mochizuki T 1999 advanced Technology of Plasticity
[11] Gantner P, Bauer H, Harrison D K and De Silva, Anjali K. M. 2004 8th International LS-Dyna Users Conference
[12] Guo X, Ma Y, Chen W, Xiong H, Xu Y, El-Aty A A and Jin K 2018 Journal of Materials Processing Technology 255 137–49
[13] Beulich N 2016 Simulation des Freiformbiegens von Profilrohren im Automobilbau: (eng. simulation of the free-bending technology of tubeprofiles in the automotive industry) (Montanuniversität Leoben)
[14] Beulich N, Craighero P and Volk W 2017 J. Phys.: Conf. Ser. 896
[15] Kane V E 1986 Journal of Quality Technology 18 41–52
[16] Maker B and Zhu X 2000 Input Parameters for Metal Forming Simulation using LS-Dyna
[17] LSTC 2016 LS-DYNA User’s Manual Volume I
[18] LSTC 2016 LS-DYNA User’s Manual Volume III
[19] LSTC 2014 LS-Dyna - Theory Manual
[20] Chernov N 2010 Monographs on Statistics and Applied Probability, Volume 117
[21] LSTC 2015 LS-OPT User’s Manual (Livermore, California)