# Investigation of the Influences on the Indentation of tubes under lateral loads by segmented forming tools using DoE

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**Abstract.** Making the widely used bending processes with geometry-specific tools, such as compression bending, more flexible in terms of the part geometries that can be produced with a single tool set, is a current challenge as mass customization and small batch sizes demands on manufacturing technologies. One approach is to segment the tools and thus add degrees of freedom that allow the die to adapt to different part geometries. However, the discrete surface can cause part defects such as localized indentations and until now, there has been no design method for segmented surfaces. As a step to close this gap, this study presents a statistical, finite element (FE) simulation-based design of experiments (DoE) to investigate the main influences on the indentation depth in the lateral indentation of circular steel tubes by segmented tool surfaces, considering both tool surface parameters and tube properties. The resulting regression equation is then used to compare the prognosticated indentation depths with those obtained from FE simulations and to develop a first pre-design approach for segmented tool surfaces. The results of the simulation-based DoE show that the segment spacing, the wall thickness factor, the interaction between them, the segment radius and the interaction between the segment radius and the segment spacing are the main influencing parameters and, interestingly, the mechanical tube properties have no significant influence. Finally, it is outlined that the regression equation can be used as a pre-design tool and that refinements are necessary for its usage as a valid design tool.

## Introduction

Megatrends are very long-term, dominant economic and social developments [1]. From the point of view of production technologies, the megatrends of neo-ecology, connectivity and individualization in particular open up challenging fields of action for industry and research [2]. Sustainability is the paradigm of our time, against which every product and the production systems required to manufacture it must be measured. According to *Stock et al.* [3], the connected *Industry 4.0* with its smart factories offers opportunities to make production sustainable and at the same time to meet the individualized customer demands. This mass customization requires highly flexible, smart manufacturing systems, not least in metal forming [4].

Considering profile bending processes, we can distinguish between kinematic processes or those with generic tools respectively on the one hand and processes with geometry-specific tools on the other hand [5]. Kinematic processes (e.g., three-roll push bending) are much more flexible in terms of the variety of part geometries that can be produced with a single tool set due to their shape-defining, free tool movement. In contrast, processes using geometry-specific tools (e.g., rotary-draw bending, compression bending) are limited in this way. However, these processes are widely used in industry because of their advantages in process controllability, dimensional part accuracy and the ability to form strong curvatures. Consequently, adjustable forming tools are needed to make geometry-specific processes more flexible while maintaining their advantages.

In a previous work, the authors have defined three levels of tool flexibility based on the scale of surface adjustment and on its impact on the process [6]. While the required surface adjustments in the range of tenths of millimeters at the first level of flexibility, which is used for example to control the material flow in deep drawing by means of adjustable blankholder systems [7], could be realized by elastic tool deformations, at the second level of flexibility, adjustments in the millimeter range to compensate for springback or to adapt the tools to different workpiece dimensions, require other tool structure concepts and design methods as presented for example by *Heftrich et al.* [8]. The third flexibility level, the reshaping of the entire tool contour, requires large tool adjustments. For this, some kind of break-up or segmentation of the conventionally closed tool surfaces is necessary, as seen for example in multi-point forming (MPF) techniques [9, 10] or as shown in *Reuter et al.* for compression bending [11]. However, the discrete tool contact can cause defects such as local indentations, wrinkles and shape deviations [11,12].

Since MPF has been used in industrial and research applications, it has been investigated mostly for large-sized parts, not for profile bending with small bending radii. Although some work has focused on the influence of the geometry of the discrete surface on part defects such as dimples, until now there is no design method for tool surface segmentation. As a step towards closing this gap, this contribution presents a design approach based on a statistical regression model. First, a validation of a FE-model based on experiments on the lateral indentation of segments and segmented surfaces in circular tubes made of E235 +N/+C steel is shown. Afterwards, a statistical design of experiments (DoE) of geometric surface parameters and tube properties is performed with respect to the quality criterion "indentation depth" as output based on FE simulations in order to obtain both, an insight into the main influencing parameters and a linear regression model. The statistical regression model is finally used to develop a pre-design rule for geometric surface parameters as a function of tube properties, which is again compared with the results from FE simulations.

## Validation of the FE-models

Lateral indentation tests on circular tubes have been performed using the *Zwick Roell Z250* universal testing machine to characterize the load-deformation behavior and to validate FE models, see also [13]. Steel tubes of grade E235 +N/+C with a circular cross section, a constant outer diameter of $D$ = 30 mm, but various tube lengths and wall thicknesses of $t$ = 1.5 mm, 2.0 mm and 3.0 mm are used as test material. Fig. 1 shows the test setup, used in [13] also. Straight segments with different radii represent the segmented tool surface and can be placed with different spacings in a fixture. A *Gom Aramis 12M* DIC system with a calibrated field of view of 200x147 mm$^2$ (resolution of 20.5 pixels/mm) is used to measure the strain distribution on the specimen surface

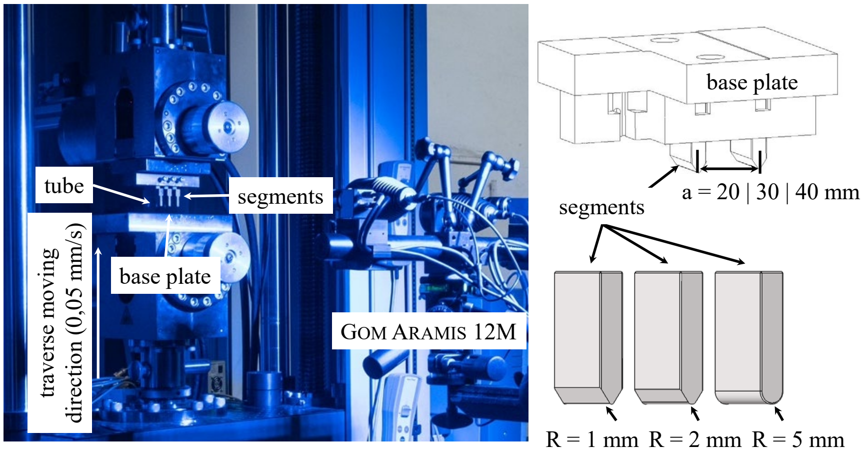
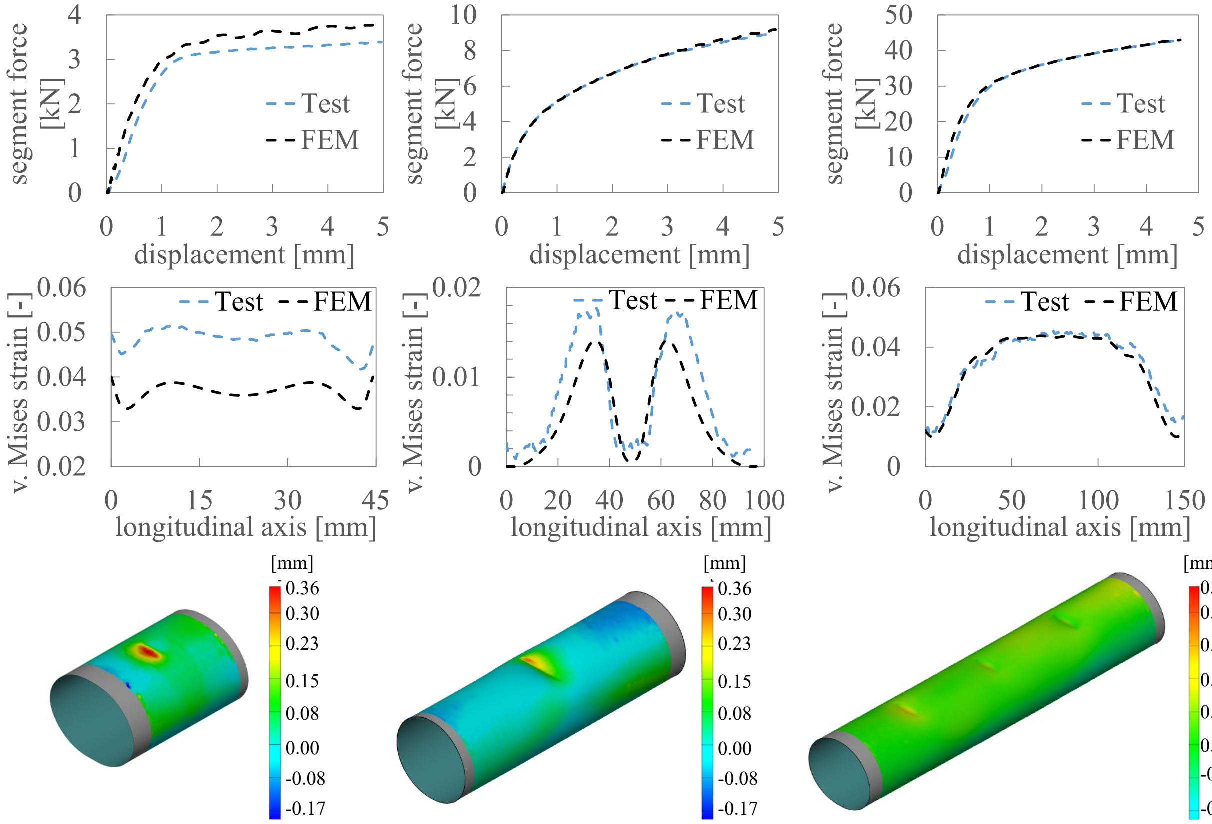


*Fig. 1: Test setup for the lateral indentation tests according to [13].*

and to measure the local tool displacements based on the applied reference points, together with the coupled 0-10 V DC force signal from the testing machine, allowing for the determination of a local force-displacement curves with eliminated system stiffness.

The FE solver *LS-Dyna R 12.0.0* is used for the simulations. The choice of the model parameters, which are described in [13] in detail, is based on a comprehensive sensitivity analysis. The tube is discretized with fully integrated hexahedral solid elements with a nominal element size of 0.5 mm in the square and 5 elements over the thickness. The isotropic v. Mises plasticity model is used, while the segments are discretized with constant stress tetrahedral solid elements and a linear elastic material law is applied. The base plate is modeled as a rigid surface with shell elements. The required flow curves were determined in uniaxial tensile tests on circular tubes and were approximated by using the El-Magd approach with approximation parameters determined by curve fitting using least-squares optimization. To simulate the contact between the tool and tube, the one-way surface-to-surface forming contact with a static Coulomb friction coefficient of 0.1 is used. Fig. 2 shows the comparison between selected experimental data and the numerical results.



(a) $t$ = 1.5 mm, $L$ = 45 mm, $R$ = 5 mm

(b) $t$ = 2.0 mm, $L$ = 97.5 mm, $R$ = 2 mm

(c) $t$ = 3.0 mm, $L$ = 150 mm, $R$ = 5 mm, $a$ = 40 mm

*Fig. 2: Comparison of results from experiment and FE simulation of lateral indentation of tubes by segments and segmented surfaces in terms of force-displacement curves (top), v. Mises strain paths along the longitudinal axis in the center of the tube on its surface (middle) and in terms of surface deviation of the resulting part geometries (bottom). The tubes are steel tubes of grade E235+N/+C with a nominal outer diameter of D = 30 mm, different nominal wall thicknesses t and different tube lengths L. Also, different segment radii R and segment spacings a are used, cf. Fig. 1.*

The FE simulations are compared with the experimental results based on the force-displacement curves (top), the DIC measurements (middle) and on the surface deviations (bottom) between the simulated and experimental geometries. The comparison of the v. Mises strains from experiment and simulation is done based on paths along the tube axis in the center of the specimen. To obtain the surface strains from the simulation with solid elements, thin shell elements with a thickness of 0.001 mm were created and evaluated along this path on the surface. To obtain the strain path from the DIC measurement exactly in the center of the specimen, an analysis coordinate system is defined in the initial configuration in the *Gom Correlate* software, based on a fitting cylinder to the undeformed tube specimen. To compare the part geometries, the deformed specimens were digitized with a *Gom Atos Core* 3D-scanner, and the surface comparison is done with the *Gom Inspect* software.

The force-displacement curves show a very good correlation between experiment and simulation, only in Fig. 2a small deviations can be observed. In addition, the v. Mises strain in the center of the tube along the longitudinal axis measured by DIC generally agrees well with the calculated values. However, the simulation underestimates the measured strain, except for the tube with a wall thickness of 3.0 mm, where no significant differences are observed. The surface deviations of the part geometries after springback between the tests and simulations show good correlations with maximum deviations of about 0.36 mm. Overall, there is a good correlation between the test data and the numerical results. Concluding, the FE model is capable of reliably predicting the load-deformation behavior of circular steel tubes in lateral indentation and thus can be used for further virtual investigations in this study.

## Methodology

To develop a design method for segmented tool surfaces, it’s crucial to know which surface parameters mainly influence the quality of the part, taking into account the tube properties. Therefore, we perform a sensitivity analysis using a statistical DoE approach on the lateral indentation of tubes by segmented tools. In fact, the seven potential influencing factors defined for this study would lead to 129 runs including the central point within a full factorial DoE. In our procedure, which will be explained in detail later, this would cause 258 simulations. To reduce the number of simulations, we use a ¼ fractional DoE with two factor levels and one central point and we focus on circular steel tubes. Fig. 3 shows the factors and the output of our DoE.

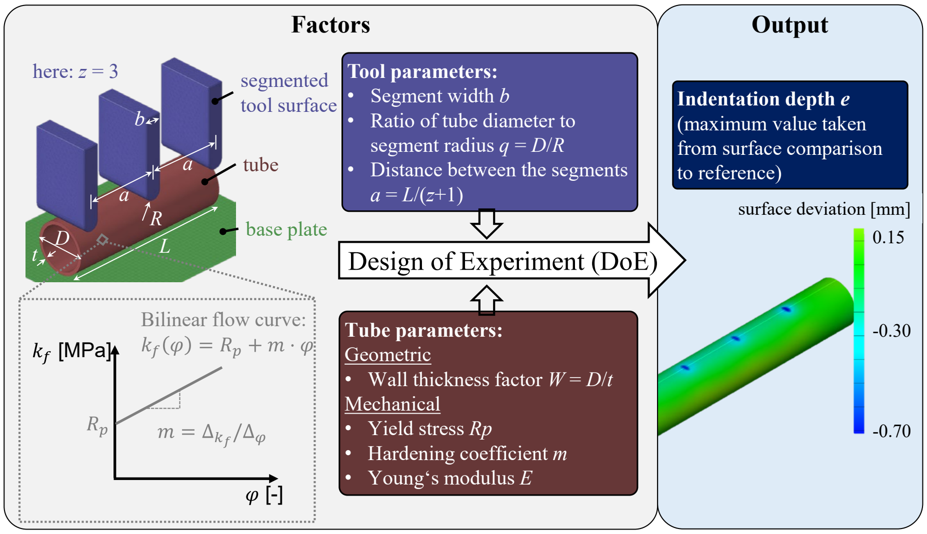


*Fig. 3: Factors and output of the simulation-based Design of Experiment (DoE) on lateral indentation of tubes by segmented tool surfaces.*

Since several authors have pointed out that in bending processes not the whole die surface is in contact with the workpiece, but only some parts [8,14], and in addition with regard to the required adjustability of the forming tools not only with respect to the bending line, but also with respect to the diameter, we choose non-enclosing surfaces. On the part of the segmented tool surfaces, the parameters are the segment width $b$, the ratio $q$ of the tube diameter $D$ to the segment radius $R$ and the distance $a$ between the segments. The tube length $L = 200$ mm and the outer diameter $D = 30$ mm are kept constant, so that the variation of $q$ and $a$ is achieved by the variation of $R$ and the number of segments $z$ within the given tube length $L$. On the part of the tube parameters, we distinguish between geometric and mechanical parameters. The geometric parameter is the wall thickness factor $W = D/t$, which is defined as the ratio of the tube diameter $D$ to the wall thickness $t$ [15]. The mechanical behavior of the tube material is parameterized by a bilinear flow curve approximation, which allows us to vary the material stiffness, strength and strain hardening behavior with only three scalar parameters in the simulation environment. While there are many quality criteria, that could be considered as output, in this paper we focus on the local indentation depth.

Table 1 shows the range of values for the factors used for the DoE. As we are focusing on steel tubes, the Young's modulus $E$ covers the typical range of different steel grades, while the yield stress $R_p$ and the linear hardening coefficient $m$ cover a wide range of steel grades with very different strength and hardening behavior as investigated in [16]. The value $q = 0$ means that the segment radius $R \rightarrow \infty$, so that it is flat surface.

*Table 1: Value range of factors used for the DoE. The tube length L = 200 mm and tube diameter D = 30 mm are indirect parameters and are kept constant.*

| | Factor | Min | Mean | Max |
|---|---|---|---|---|
| Tube | Wall thickness factor $W = D/t$ [-] | 10 | 20 | 30 |
| | Yield stress $R_p$ [MPa] | 200 | 467.5 | 735 |
| | Linear hardening coefficient $m$ [MPa] | 850 | 1900 | 2950 |
| | Young's modulus $E$ [GPa] | 195 | 205 | 215 |
| Tool | Ratio $q = D/R$ [-] | 0 | 3 | 6 |
| | Segment width $b$ [mm] | 5 | 7.5 | 10 |
| | Distance between the segments $a = L/(z+1)$ [mm] | 12.5 | 25 | 40 |

The procedure to obtain the output values according to the parameter variations from the DoE is shown in Fig. 4. Initially, for each combination of tube parameters, a reference simulation is performed with an imposed velocity and two opposing plates as the closed tool surface. In the second step, a collapse force $F_{\text{collapse}}$ is extracted from the resulting force-displacement curves, which represents the transition between elastic and plastic cross-sectional deformation. In order to determine the collapse force consistently for each parameter set, a criterion has been defined. Straight lines are fitted to the linear elastic and linear plastic regions. The force at the intersection of another straight line, which is orthogonal to the linear curve fit to the plastic region and passes through the intersection of both linear curve fits, and the force-displacement curve is defined as the collapse force. Third, the segmented tool surface with the DoE parametrization is loaded by this collapse force. We choose this load case for a very specific reason. Considering the long-term goal of this research, the development of a design method for segmented bending tool surfaces, the global load of the bending die for a dedicated bending process is predefined by the bending task (bending radius, wall thickness factor, mechanical material properties). Therefore, the load case must be an imposed force and the local indentations must be induced mandatorily. Thus, the collapse force is the global load, that the specific tube can just withstand without cross-sectional plastic deformation, so to speak a forming process with a resulting in-specification part. By reducing the contact area through segmentation, the local contact pressure arises, local indentation occurs and the impact of the influencing parameters on their value can be investigated.

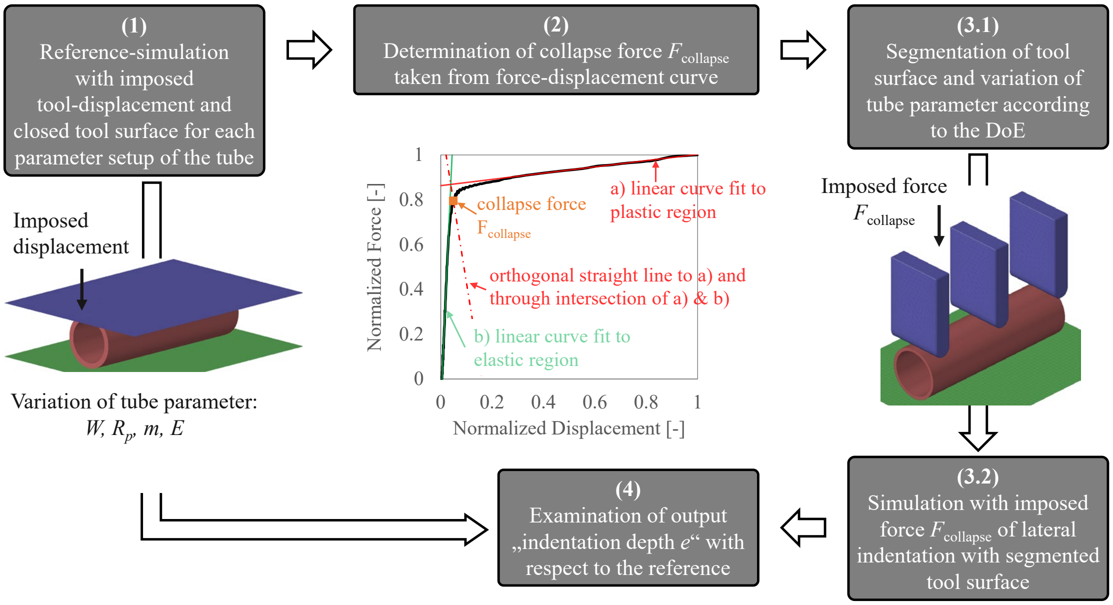


*Fig. 4: Procedure for performing the simulation-based DoE.*

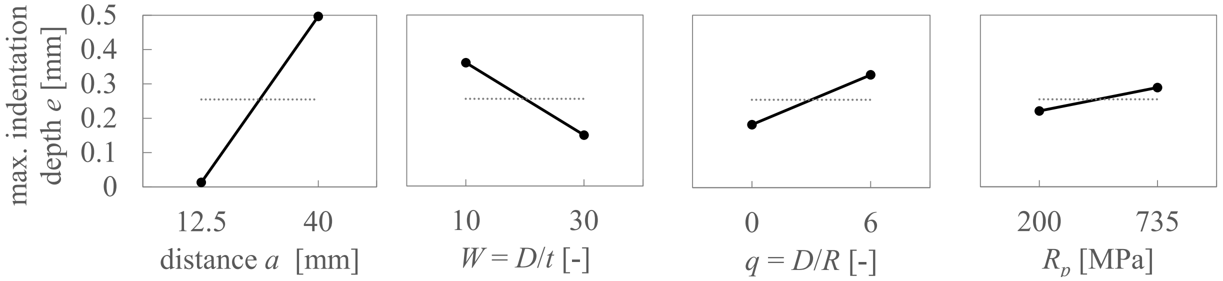
The last step in our procedure is the examination of the local indentations with respect to the reference simulation by means of surface comparison analysis using *Gom Correlate 2021* software.

## Results

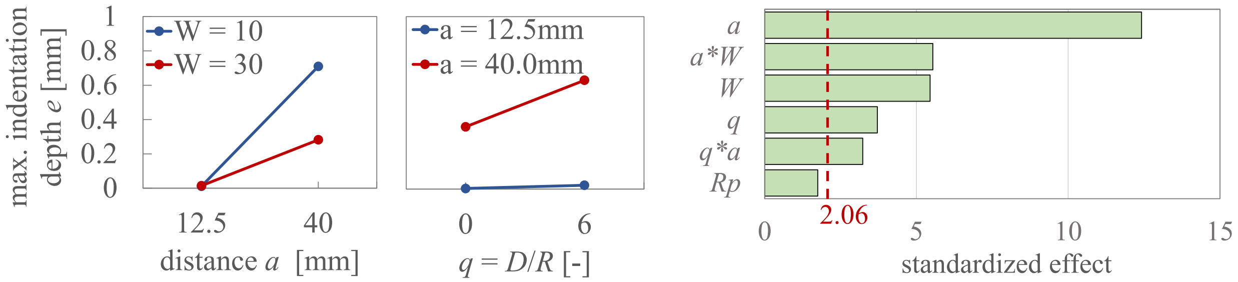
*Minitab Statistical Software* is used to perform the statistical analysis of the experimental design. The selection of the factors and the interactions that are part of the linear regression model is done in a hierarchical procedure based on the p-values with a confidence level of $\alpha = 0.05$. This means that factors and interactions are systematically eliminated from the model until the model consists only of statistically significant parameters. The main effects of the factors that are part of the generated regression model are shown in Fig. 5a. It is observed that the indentation depth $e$ increases as the segment spacing $a$, the ratio $q$ and the yield stress $R_p$ increase. Furthermore, the indentation depth increases as the wall thickness factor $W$ decreases, that means that the indentation depth increases with increasing wall thickness. The slopes of the straight lines in the main effect diagrams indicate the strength of the effect. Additionally, Fig. 5b shows two statistically significant interactions. One is the interaction between the segment spacing and the wall thickness factor. Increasing segment spacing results in considerably greater indentation depths for a wall thickness factor of $W = 10$ compared to $W = 30$. Secondly, there is an interaction between the ratio $q$ and the segment spacing $a$. While the segment radius has hardly any influence on the indentation depth for a small segment spacing, it has an even greater influence for large segment spacings. Finally, the Pareto diagram of the standardized effects of the individual factors and the interactions shows a ranking of the influencing parameters. Note, that the influence of the yield strength is not statistically significant, but still has a sufficiently large influence. It was also included in the regression model because it slightly improves the prediction quality of the model. The regression equation of the statistical model for the indentation depth follows

$$e = c_0 + c_1 \bullet a + c_2 \bullet W - c_3 \bullet a \bullet W - c_4 \bullet q + c_5 \bullet q \bullet a + c_6 \bullet R_p, \tag{1}$$

with the constants $c_0 = -0.418$, $c_1 = 0.02868$, $c_2 = 0.00999$, $c_3 = -0.000784$, $c_4 = -0.0159$, $c_5 = 0.001523$ and $c_6 = 0.000127$. The prognosticated mean square deviation $R^2$ between the model and the experimental values is $R^2 = 0.85$, whereby the central point is not part of the model because its consideration worsens the model quality.



(a) Main effect diagrams



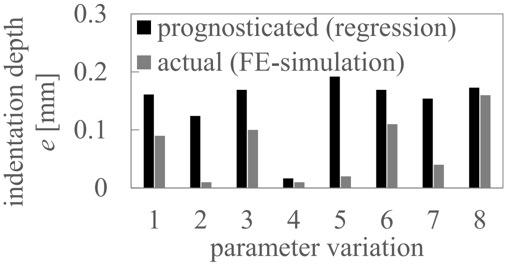
(b) Statistically significant interactions

(c) Pareto diagram of standardized effects with a confidence level of $\alpha = 0.05$

*Fig. 5: Results of the statistical analysis of the simulation-based DoE on lateral indentation of circular steel tubes by segmented surfaces.*

Even if the predicted $R^2$ value initially promises a sufficiently good predictive capability of the model regarding the target variable "indentation depth $e$", there are some critical points to consider when using the model. Non-linearities occur in the underlying problem of lateral indentation of tubes by means of segmented tool surfaces. Although the elastic and plastic deformation behavior in the simulations of this study is linear due to the chosen material parameterization (bilinear flow curve approximation, see Fig. 3) the geometric deformation of the entire tube cross-section over the tube length as well as the local deformation in the contact zone is non-linear. The contact between the tool and the tube causes additional non-linearity. However, with the ¼ fractional design of experiments, only a linear regression model can be generated, which means that the actual non-linearity of the problem is not taken into account. In addition, some parameter combinations are missing due to the reduced factorial experimental design, which means that not any possible influencing variables and interactions, especially higher order interactions, are captured.

Knowing these systematically introduced uncertainties, the regression model is subsequently used on the one hand to compare the predicted indentation depths with those obtained from the FE simulations. On the other hand, it is investigated to what extent it is possible to predict segmented tool surface parameter based on the regression model. For this purpose, the workpiece parameters and the segment width are specified as the only tool parameters and the two remaining tool parameters, namely the segment radius ratio $q$ and the segment distance $a$, are determined with respect to a specified maximum indentation depth of $e_{\text{allowed}} = 0.2$ mm using least squares optimization. Fig. 6 shows the chosen and optimized tool and workpiece parameters on the right and the comparison between the indentation depths from the regression model and the FE simulation on the left. The indentation depths from the FE simulation are determined according to steps (3.2) and (4) from Fig. 4.



| | | Parameter variation | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| choosen parameters / least square optimized parameters using regression model for $e_{\text{allowed}} = 0.2$ mm | ***W*** **[-]** | 30 | 10 | 30 | 30 | 10 | 10 | 10 | 30 |
| | $R_p$ **[MPa]** | 735 | 200 | 200 | 735 | 735 | 200 | 735 | 735 |
| | ***m*** **[MPa]** | 885 | 850 | 850 | 2950 | 850 | 850 | 850 | 2950 |
| | ***E*** **[GPa]** | 215 | 215 | 195 | 195 | 195 | 215 | 195 | 195 |
| | ***b*** **[mm]** | 5 | 10 | 5 | 5 | 10 | 10 | 10 | 5 |
| | ***q*** **[-]** | 6 | 0 | 6 | 15 | 0 | 3.05 | 3.3 | 3.1 |
| | ***a*** **[mm]** | 20 | 20 | 25 | 10 | 20 | 20 | 16.7 | 25 |
| imposed collapse force | $F_{\text{collapse}}$ **[kN]** | 9.3 | 31.9 | 3.1 | 9.8 | 106.2 | 31.9 | 106.2 | 9.8 |

*Fig. 6: Comparison between the indentation depths prognosticated by the regression model and determined in the FE-simulations (left) and corresponding parameter variations (right).*

When comparing the indentation depths from simulation and regression in Fig. 6, it is noticeable that the regression model always predicts larger values than those obtained from the FE simulations. The ratio between the prognosticated value and the actual value ranges from 1.08 (parameter variation 8) to 12.41 (parameter variation 2) and is 4.20 on average for all variations performed. This indicates that the regression equation in this form cannot yet be used to make valid quantitative statements about the expected indentation depth. However, since the predicted values for the parameter sets considered here are always significantly greater than the calculated indentation depths from the FE simulations, the regression model can be used as a pre-design tool for the segmentation of tool surfaces.

## Conclusions

Since mass customization is an increasing demand for production technology, flexible manufacturing processes are needed in metal forming. While kinematic bending processes have inherent flexibility due to their shape-defining tool motion, the widely used tool-related processes are limited in this way. One approach to making them more flexible is to segment the closed tool surfaces, which adds degrees of freedom to the tool and allows it to adapt to different part geometries. However, these discrete surfaces can affect the quality of the part, in particular causing localized indentations. Although multi-point forming techniques have been investigated for a long time, until now there is no design approach for segmented tool surfaces that takes into account the properties of the workpiece and the boundary conditions.

In this study, the authors have presented a statistical, FE simulation-based design of experiments (DoE) to investigate the main influences on the indentation depth in the lateral indentation of circular steel tubes by segmented tool surfaces. Since valid data are required for the statistical evaluation, we first validated the FE model through experiments on lateral indentation of tubes by segmented tool surfaces in terms of the features force-displacement curves, strain distributions, and the resulting part geometries. The regression equation of the statistical model is then used to compare the prognosticated indentation depths with those obtained from FE simulations and to develop a first approach for the pre-design of segmented tool surfaces for an allowable indentation depth $e_{\text{allowed}}$. Finally, the predicted indentation depths from the regression model are compared with those obtained from the FE simulations. A graphical summary of the procedure followed in this paper is given in Fig. 7.

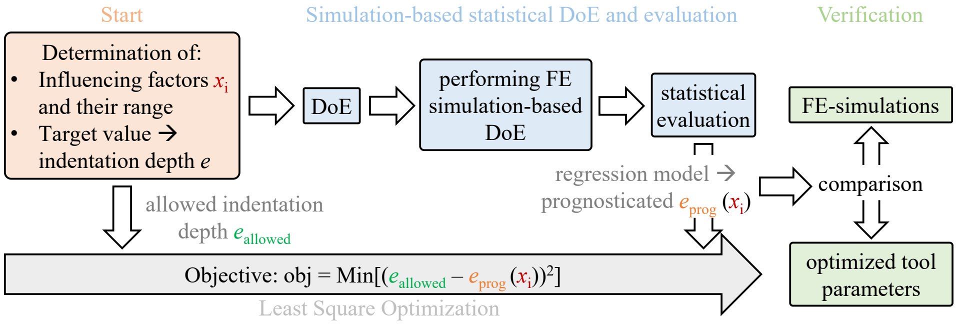


*Fig. 7: Summary of the procedure followed in this paper.*

The FE simulations of the lateral indentation show a very good correlation to the experiments and can therefore be used as valid digital twins for the following simulation-based DoE. Of the seven potential influencing parameters defined, the segment distance *a*, the wall thickness factor *W* and the interaction between *a* and *W* have the largest influence on the indentation depth *e*. The ratio *q* of tube diameter to segment radius and the interaction between *q* and *a* also have a statistically significant influence. Although the resulting regression equation has a $R^2$-value of 0.85, the prognosticated indentation depths differ considerably from those obtained from the FE simulations. This could be due to the chosen ¼ fractional experimental design, which lacks ¾ of the possible factor combinations and allows only linear regression models to be conducted, while the actual problem is nonlinear in character. However, the prognosticated indentation depths are always greater than the simulated ones. Therefore, the regression model can be used as a pre-design tool for segmented tool surfaces. Future work has to focus on improving the statistical model. This could be done by using only the statistically significant parameters for further full factorial DoE. Another option is to use sequential design of experiments (SDoE) approaches, which improve the model quality by gradually refining the sets of space-filling input parameters.

Indeed, this study considers the lateral indentation of segmented surfaces on tubes lying on a flat plate. Nevertheless, very important information can be derived from this study also for the segmentation of bending tools, which is the goal of our research project. It is shown that the mechanical properties of the tube have no or negligible influence on the local indentation. Instead, the wall thickness factor as geometric parameter has a large influence. This significance and that of the surface parameters as well as the interactions that have been identified will also be transferable to bending processes to a certain extent, although it should be noted that the process boundary conditions in the form of compressive stresses at the inner arch will influence the indentation depth.

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