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Influence of Process Parameter Variations on Stamping-Bending Component Quality

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Abstract. Achieving high geometric accuracy is crucial in stamping and bending processes. Key influencing factors include the position of the blank within the coiled sheet, leveling, strip lubrication, contour cutting, and the bending sequence. Currently, process design and parameter selection rely largely on the expertise of experienced engineers. A data-driven approach requires a detailed analysis of the effects and interactions of all process parameters. This analysis must include parameter settings, machine data and measurements of all manufactured parts. This study presents variance, interaction, and quality analyses based on long-term production trials for busbars. Process parameters were combined according to a statistical experimental design. The results indicate positive effects from slight pre-bending of sheet strips, active leveling, material removal through contour cutting, and simultaneous bending operations.

Introduction

Stamping-bending components are typically produced from sheet coils through multiple stamping and bending operations in a single pass on automated stamping and bending machines. Common products with complex geometries include electrical conductors, terminals, contacts, and spring elements [1]. Component geometry is achieved either by loading beyond the yield strength or by modifying an already plastic state. Dimensional accuracy is critical for component quality and is strongly influenced by springback, residual stresses, bending sequence, and process uncertainties [2]. These uncertainties arise from material variations and interactions between process steps. To date, process design has relied heavily on implicit knowledge from experienced toolmakers and engineers. Such uncertainties, often referred to as process noise, should be captured and addressed by integrating sensors into the process chain. Understanding interactions within stamping-bending processes and assessing their generalizability is essential. While simulation approaches exist, FEM models are typically optimized for specific applications, limiting their broader validity. Therefore, statistical evaluations of data collected along the process chain and on finished components offer significant potential. They can reveal interactions between influencing parameters and resulting component properties. This enables inverse process tracing to determine the root causes of manufacturing quality for each part.

Approach

Experimental Setup.

A busbar is selected as the test component to analyze the influence of process parameters on geometry. Manufacturing is carried out on a Bihler GRM-NC stamping-bending machine, combining leveling, lubrication, cutting, free-form bending, and die bending operations (see Fig. 1). The machine is supplied with EN AW-5754 H22 aluminum alloy in strip form from a coil. An activatable leveling process allows sheet strips to be flattened through alternating cold forming. Strip lubrication can be switched on or off via two rollers, using CLF 49 oil to prevent aluminum flake formation and adhesion. After the feed unit, the stamping unit punches pilot holes, cuts contours, and separates workpieces by shearing. The four cutting punches can be removed at any time to analyze the effect of contour cutting on component properties. The final module is a bending station, where the two legs of the busbar are first pre-bent freely. In the last step, the middle section is bent using a die, after which the finished busbar is ejected.

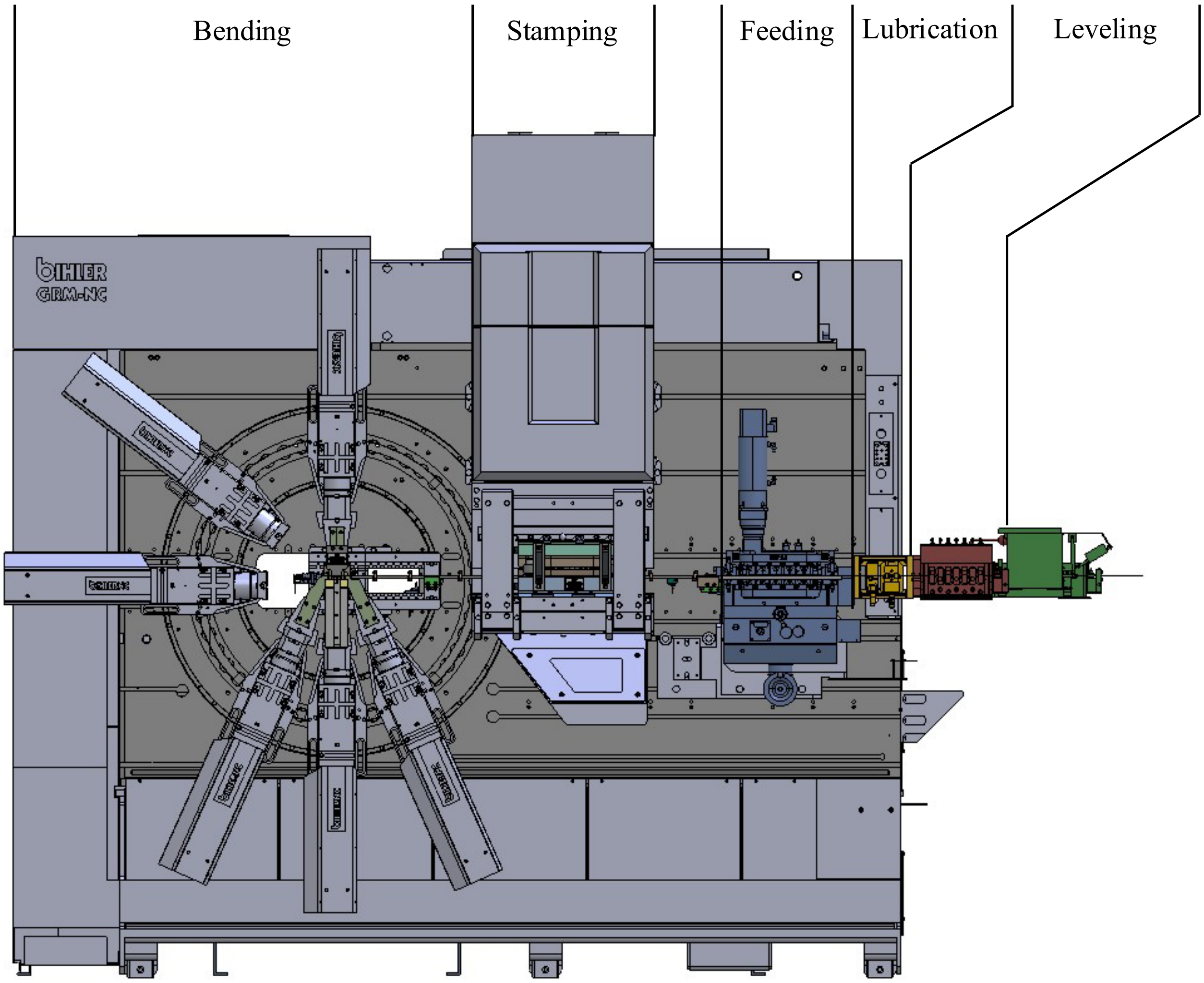


Fig. 1. Manufacturing stations for busbar production on the Bihler GRM-NC stamping and bending machine.

The transformation of the component throughout the individual process steps is illustrated in Fig. 2. Initially, positioning holes are punched during the cutting operations, followed by contour cutting in a single stroke. In the third step, the connection surfaces of the busbar are pre-bent at both flank angles to ensure proper alignment. After the final step of die bending of the central section, the finished component contour is obtained.

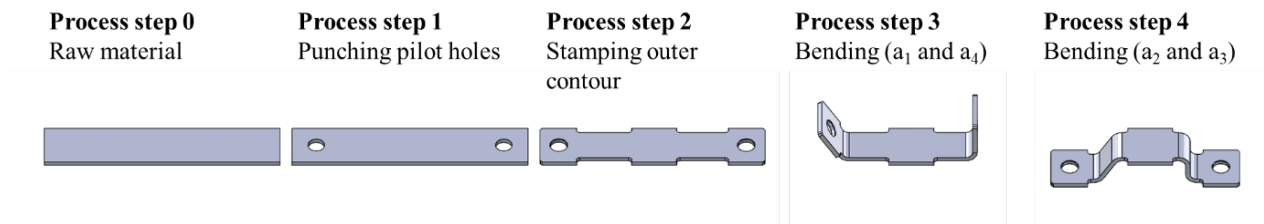
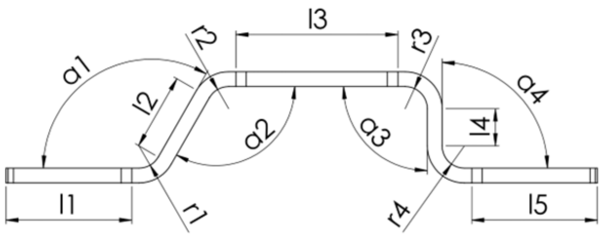


Fig. 2. Process steps in busbar manufacturing.

To enable a consistent quality assessment, a standardized geometric parameterization of the busbar is required. Therefore, the five planar sections are defined as lengths l_1 to l_5 , the internal angles as a_1 to a_4, and the corresponding radii as r_1 to r_4 (see Fig. 3).



Parameter	Description
$l_1, \ldots, l_5$	Length
$a_1, \ldots, a_4$	Bending angle
$r_1, \ldots, r_4$	Bending radius

Fig. 3. Geometric parameterization of the busbar.

The target values corresponding to the 13 parameters are listed in Table 1. These values form the basis for designing the CAD model and the associated manufacturing process of the busbars.

Table 1. Nominal target values for the geometric parameters of the busbar.

Parameter	Unit	Target value
Length l_1	mm	18,00
Length l_2	mm	10,40
Length l_3	mm	23,90
Length l_4	mm	5,00
Length l_5	mm	18,00
Angle a_1	°	120,00
Angle a_2	°	120,00
Angle a_3	°	90,00
Angle a_4	°	90,00
Radius r_1	mm	3,00
Radius r_2	mm	3,00
Radius r_3	mm	3,00
Radius r_4	mm	3,00

These parameters are used to evaluate the manufacturing quality of each component based on its relative deviation from the nominal values. Combined with machine data and process settings, these measurements allow the identification of interactions between influencing factors. Dimensional measurements are performed using the in-line inspection system developed by Martinitz et al. [3]. Components are transported via a chute to a glass angle, where grayscale images are captured by two cameras from both profile and top views. High-quality optics and backlighting are employed to ensure optimal image resolution. The images are binarized using a MATLAB script and initially analyzed with the imfindcircles function. This approach was later replaced by a gradient-based evaluation method. This method segments the component into linear sections based on its slope. Angles and radii are then calculated between these sections. The gradient-based method proved significantly more robust, as the circle detection algorithm often failed when transition zones between contour segments exhibited elliptical rather than circular shapes. Since subsequent geometric evaluation depends on accurate arc identification, such failures previously caused complete analysis interruptions.

Influencing Parameters.

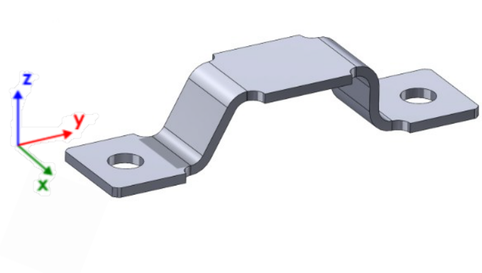
The process parameters varied in this study include leveling, strip lubrication, contour cutting, and bending sequence. These factors are combined stochastically in accordance with the principles of statistical experimental design. Table 2 provides an overview of the factors and their levels.

Table 2. Combined factors and factor levels of the Design of Experiments.

Factor	Factor level
Coil	Coil 1- beginning Coil 1- middle Coil 1- end
Leveling	activated deactivated
Lubrication	activated deactivated
Notches contour	activated deactivated
Process sequence	simultaneous left, right right, left left holding, right right holding, left

The first factor relates to coil position, which is divided into three regions: the initial third, characterized by the largest mean radius, the middle section, and the end section, where the coil radius decreases. These regions differ significantly in pre-deformation, which may affect component geometry. Quach et al. demonstrated a direct correlation between residual stresses and springback [4]. His research found that residual stresses increase as the winding radius decreases. They also found that lower material strengths are associated with higher residual stresses in the component. Lee et al. have previously analyzed the resulting stress states using numerical models [5]. They demonstrated that, without leveling, there would be an increasing deviation from the geometric target values for the component. With a correctly adjusted leveling process, however, this should not occur. Investigations show that roll leveling homogenises the uneven distribution of residual stress. Leveling and lubrication can be manually activated or deactivated at the start of each test series. Comparing components produced with and without these settings reveals their direct impact on manufacturing quality. Fig. 4 illustrates two component variants used to study the influence of outer contour modifications. Variant A features four symmetrical cutouts, while Variant B retains an unmodified contour.

Part type A:



Part type B:

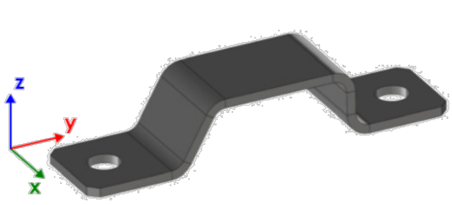


Fig. 4. Component Variant A with outer contour cut and Component Variant B without outer contour cut.

This study thereby investigates the impact of strain hardening introduced during the stamping process on dimensional accuracy, as previously examined by Bolt et al. [6]. The associated residual stresses and reduction in component volume may influence springback behavior, as demonstrated by Kumar et al. [7]. The final variable parameter concerns the bending sequence. While the last step, the die bending of the central section, is fixed, the sequence of pre-bending the busbar legs is adjustable. In this free-form bending process, the two punches can operate in different modes: simultaneously, right-first then left, or left-first then right. Alternatively, after the initial bend, the punch can remain engaged while the opposite leg is bent, resulting in five distinct bending sequences. These sequences are summarized in Fig. 5.

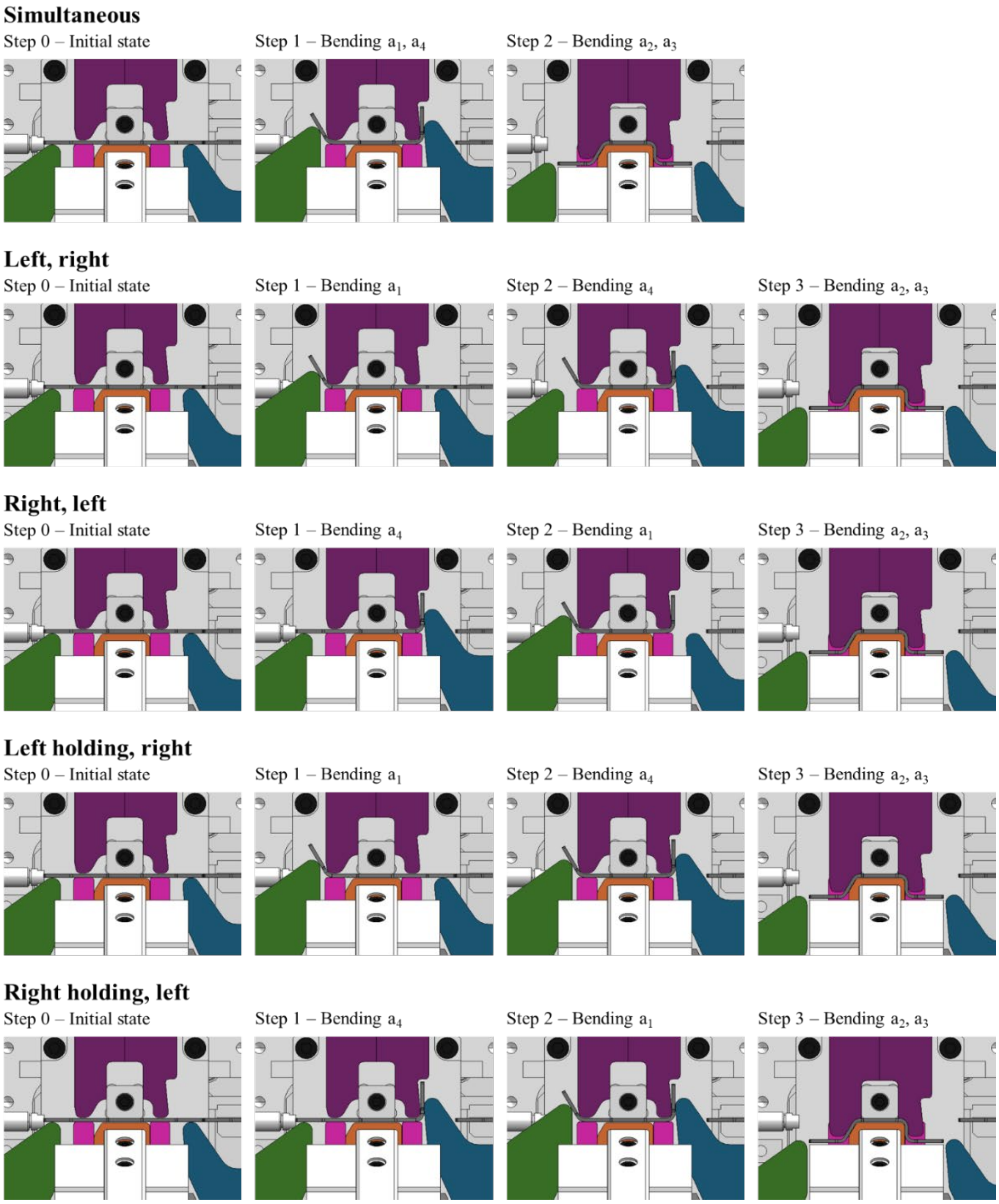


Fig. 5. Positions of the bending punches for the five different bending sequences.

Methods.

The experimental design is structured according to the principles of the Design of Experiments, following a statistically valid random sequence of test runs. Variance, interaction, and quality analyses are used to examine interactions among process, machine, and component-geometry parameters. To classify the manufacturing quality of each component using a single metric, the dimensionless Overall Quality Indicator (OQI) is introduced. For normalization across different measurement scales, a z-transformation is applied to each geometric quality characteristic of the busbar. Subsequently, the absolute values of the z-scores are summed across all component parameters. The OQI therefore quantifies the overall deviation of a component's quality characteristics from the dataset mean. A low OQI indicates consistently high product quality with minimal deviations, whereas a high OQI reflects greater variability in quality parameters. The OQI can be expressed by the following mathematical relationship:

$$\boldsymbol{OQI_j} = \sum_{i=1}^{n} \left| \frac{x_{ij} - \bar{x}_i}{s_i} \right| \quad (1)$$

where
x_{ij}= value of quality parameter i in trial j
$\bar{x}_i$= mean of quality parameter i
s_i= standard deviation of quality parameter i
n= number of quality parameters

Results and Discussion

Machine data.

Based on the torque profiles of the spindle presses and bending units shown in Fig. 6, trends can be observed throughout the long-run production trials. These trends become particularly evident when considering the cleaning interventions for the active tool elements, which are also indicated in the graphs.

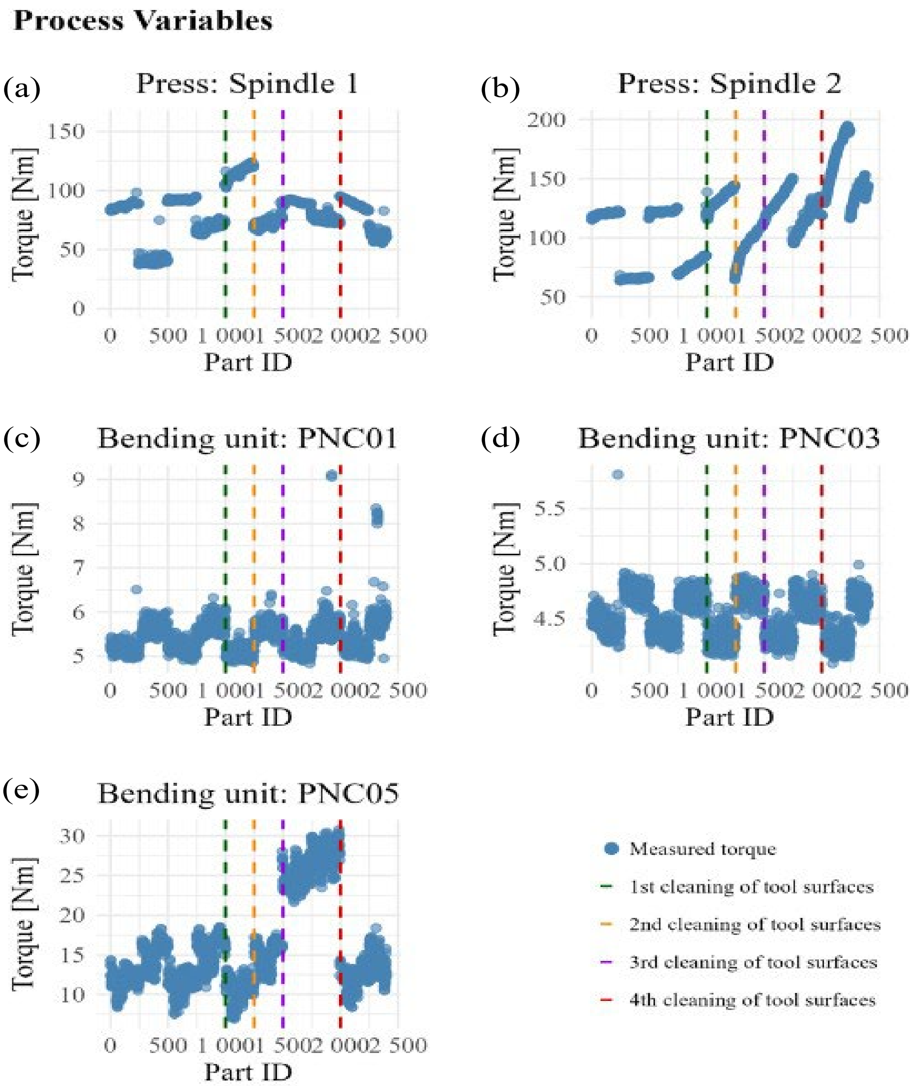


Fig. 6. Distribution of maximum torques per manufactured component at the two spindle presses for cutting (a, b), the two free-form bending axes (c, d), and the die bending axis (e).

Overall, all press spindles show about 70 % higher maximum torque when additional cutouts are stamped into the contour. Conversely, these components exhibit approximately 7 % lower torque values at the bending units, as less material mass needs to be formed. The increasing torque after each cleaning cycle is caused by aluminum adhering to the tool surfaces. The adhesion reduces the cutting clearance and increases friction in the punch guides, resulting in higher process forces. After a certain number of produced parts, removal of these adhesions becomes essential, as the tool halves can no longer be separated for maintenance and cleaning. Immersion in a 1 % sodium hydroxide solution for 2-3 hours dissolves the aluminum deposits, restoring tool functionality. However, the extent of adhesion increases after each cleaning cycle, which is reflected in the progressively steeper torque curves.

Analysis of Variance.

To evaluate the average dispersion within individual factor levels, an analysis of variance (ANOVA) is performed. The objective is to identify which level of each factor exhibits the lowest variability. Lower variability in a quality characteristic indicates a more stable process. The results for the four investigated factors in the process chain are presented in Fig. 7.

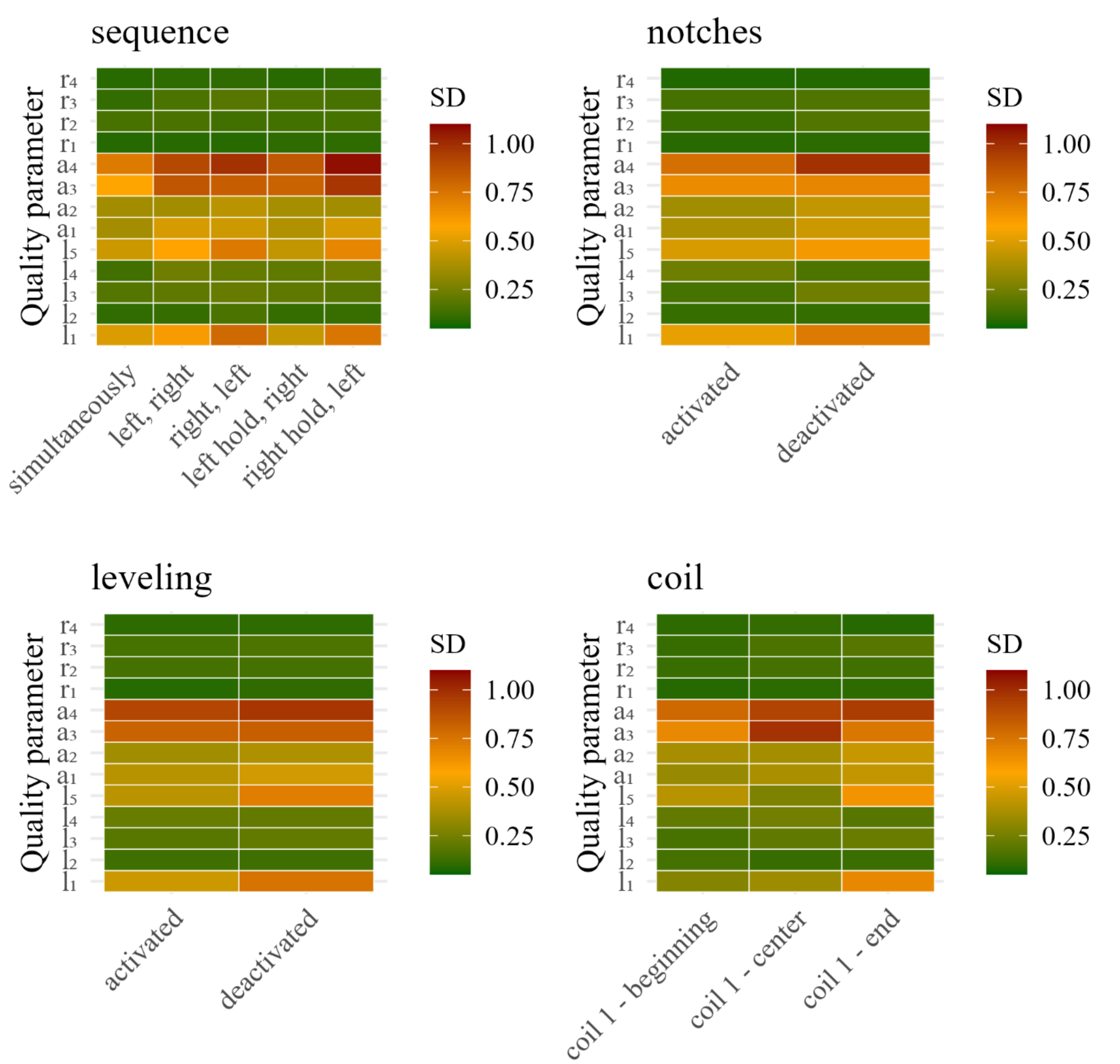


Fig. 7. Heatmaps for analyzing the variability of quality parameters for each parameter setting.

The heatmaps clearly show that all four radii and the lengths of the inner straight sections (l_2 to l_4) exhibit low standard deviations. In contrast, pronounced fluctuations are observed for all four angles as well as for l_1 and l_5. The high variability in angles is primarily attributed to springback. Standard deviations tend to be lower for bends with larger angles, i.e., those subjected to less severe deformation. The strong variation in the lengths of the two outer legs of the busbar is tool-related: when installing the entire cutting tool in the stamping-bending machine, its position along the process chain is not precisely fixed, as the distance to the part guides can be adjusted.

An isolated analysis of standard deviations under the factor bending sequence reveals that simultaneous bending provides the most stable process. Components with stamped cutouts also show reduced variability in quality parameters. For the factor leveling, angles exhibit lower standard deviations when leveling is active compared to when it is deactivated, confirming the effectiveness of leveling in reducing pre-deformation caused by coil winding. Similarly, the analysis of the coil section factor indicates that the initial coil region yields the lowest standard deviation. As coil radius decreases towards the end of the coil, standard deviations of component parameters increase, reflecting the growing pre-deformation of the strip and the resulting decline in process stability.

Interaction Analysis.

As part of the interaction analysis, the relationships between individual factors are examined. The first step focuses on how leveling and contour cutouts influence the Overall Quality Indicator at different coil positions. The interactions between leveling and coil section, cutouts and coil section, as well as cutouts and leveling, are illustrated in Fig. 8.

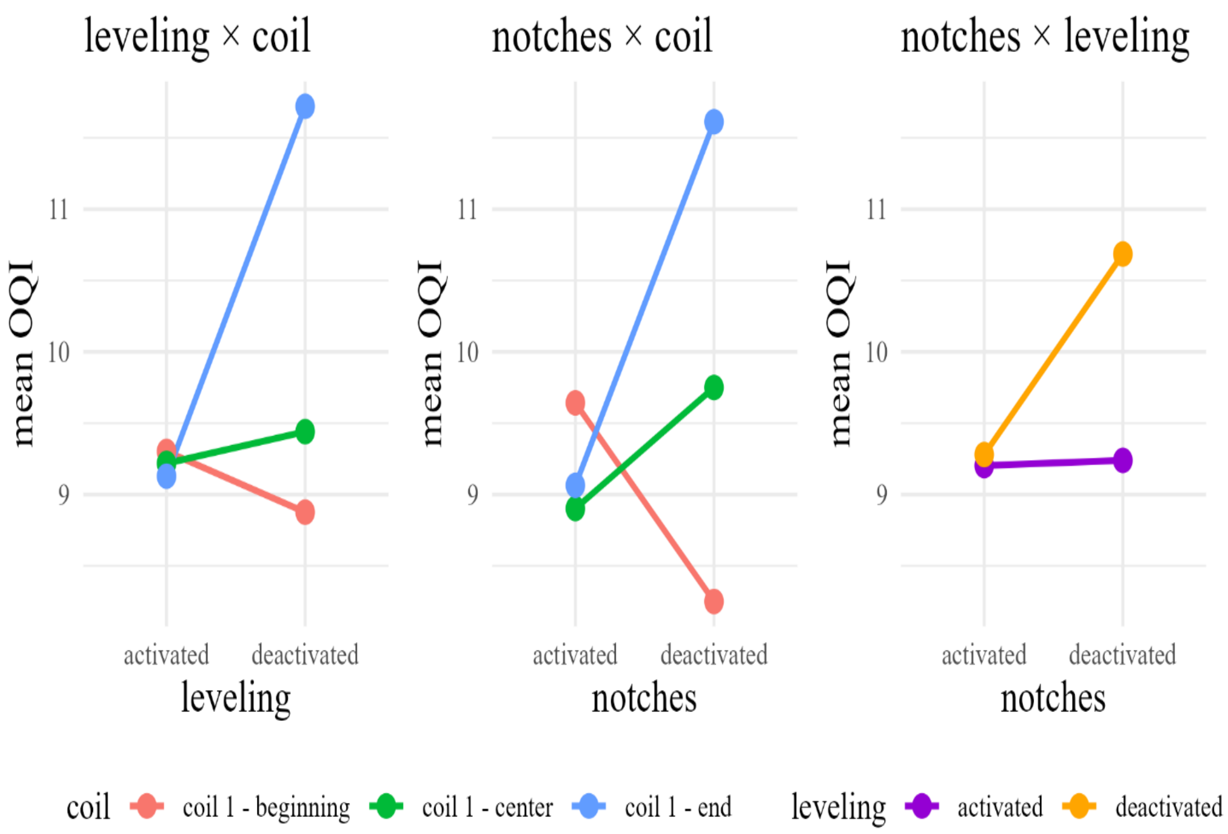


Fig. 8. Interaction analysis of the factors leveling, cutouts, and coil section on component quality.

The interaction plots between leveling and coil position show similar trends to those between cutouts and coil position. This indicates that the contour cutting process exerts a comparable influence on the variability of quality parameters as the leveling process. This is particularly evident in the interaction between cutouts and leveling. When both are activated, the OQI reaches its minimum. Subsequently, the interactions between the factor bending sequence and the remaining investigated factors are analyzed. The corresponding interaction plots are presented in Fig. 9.

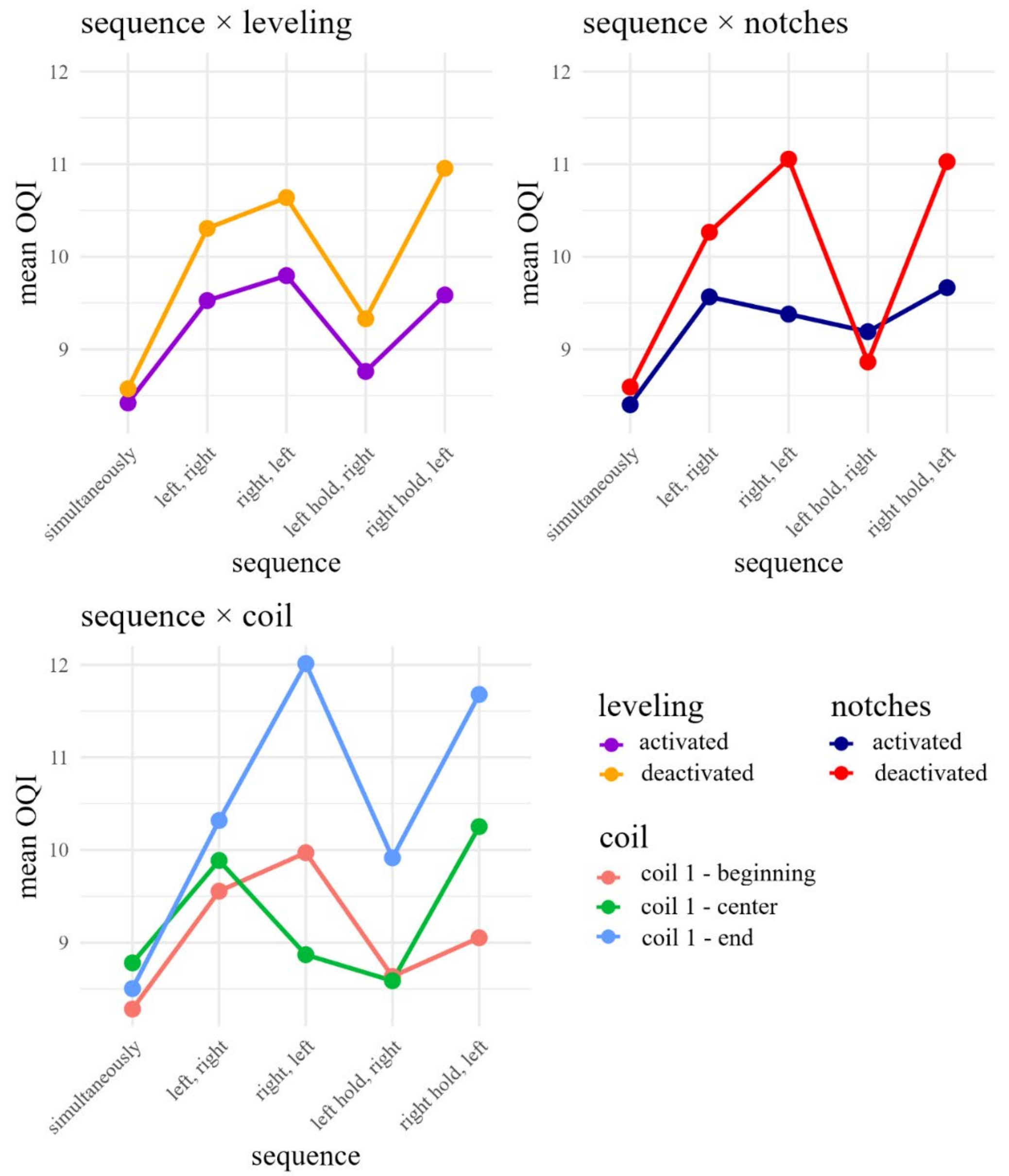


Fig. 9. Interaction analysis of the factor bending sequence on component quality.

The analysis confirms that the simultaneous bending sequence yields the lowest variability in quality parameters. In this case, the influence of leveling on the OQI is negligible. For all other bending sequences, an active leveling process reduces variability compared to a deactivated one. Similar findings emerge from the interaction between bending sequence and cutout stamping, with the exception that lower variability is observed even for the simultaneous sequence when cutouts are stamped. The cutout stamping process shows a particularly strong effect on the OQI for the right-left sequence. Conversely, an opposite trend is observed for the left hold-right sequence, where variability is lower when cutouts are not stamped. The interaction between bending sequence and coil section indicates that the simultaneous and left–right sequences are largely independent of coil position, whereas the remaining sequences exhibit a clear dependency on coil section.

Quality analysis.

The quality analysis investigates which bending sequence provides the highest process capability and process control with respect to the component bending angles. For each test series, the mean and standard deviation of the four angles are calculated. To assess process capability, the mean of the standard deviations ($\bar{s}$) of the individual angles within each test series is determined for each bending sequence. The sequence with the smallest mean standard deviation corresponds to the process with the highest capability.

Process control is quantified by the deviation of the series means from the overall mean, referred to as the mean deviation of means and abbreviated as c_μ. The sequence with the smallest average deviation represents the most controlled process. The results of the quality analysis are summarized in Table 3.

Table 3. Mean standard deviation ($\bar{s}$) and mean deviation of means (c_μ) of the bending angles for each bending sequence.

Process sequence	Parameter	$\bar{\bar{x}}$	c_μ	$\bar{s}$
simultaneous	a_1 [°]	126,02	0,198	0,270
	a_2 [°]	121,42	0,213	0,234
	a_3 [°]	97,34	0,375	0,340
	a_4 [°]	98,44	0,527	0,390
left, right	a_1 [°]	126,09	0,305	0,307
	a_2 [°]	121,16	0,162	0,277
	a_3 [°]	97,29	0,532	0,569
	a_4 [°]	97,98	0,533	0,659
right, left	a_1 [°]	126,07	0,251	0,312
	a_2 [°]	121,26	0,201	0,308
	a_3 [°]	97,48	0,494	0,545
	a_4 [°]	98,18	0,506	0,687
left holding, right	a_1 [°]	125,94	0,237	0,275
	a_2 [°]	121,05	0,168	0,293
	a_3 [°]	97,32	0,554	0,540
	a_4 [°]	97,95	0,492	0,630
right holding, left	a_1 [°]	125,93	0,268	0,336
	a_2 [°]	121,08	0,188	0,273
	a_3 [°]	97,22	0,647	0,573
	a_4 [°]	97,79	0,667	0,665

Overall, the simultaneous bending sequence demonstrates the highest process control and capability. The mean standard deviation across all angles is, on average, 32 % lower during the simultaneous bending process compared to the other bending sequences. Only for the quality characteristic a_2 do the other sequences perform slightly better. Notably, the low variations within individual test series for the simultaneous sequence indicate a high process capability. The lowest process control and capability are observed for the right hold–left sequence. This suggests that simultaneous bending ensures the most homogeneous material flow, which, according to Durmaz et al. [8], significantly influences the intensity and distribution of bending stresses.

Conclusion

This study demonstrates how insights into interactions within stamping-bending processes can be extracted from large-scale experimental data. The parameters that varied include coil section, leveling, strip lubrication, contour cutting, and bending sequence. Combined with machine data and measured component geometries, these variations enable identification of the optimal parameter combination for minimizing geometric variability. A total of 2,400 busbars were produced in long-term production trials, with parameter settings changed after every 25 parts according to a statistical design. Components were measured in-line at the end of the process using an optical inspection system, ensuring complete traceability of each part to its dataset.

The results indicate a positive effect of leveling and contour cutting on dimensional accuracy. Components manufactured with these measures exhibit lower deviations from nominal geometry and reduced variability compared to those produced without them. Furthermore, dimensional accuracy tends to decrease as coil radius decreases, due to increasing pre-deformation. Regarding the bending sequence, simultaneous bending yields the smallest mean deviation and lowest variability of measured dimensions. The mean standard deviation is thereby reduced by 32 % in the simultaneous bending process compared to the alternative bending sequences. Consequently, the highest process capability and control can be achieved with a large coil radius, active leveling, contour cutting, and simultaneous bending.

Further studies are required to verify the generalizability of these findings. These studies should include other components, extended process monitoring, and alternative inspection methods. Within the DFG Priority Program 2422 on data-driven process modeling, the experimental data will also be used to train neural networks. Machine learning will then enable the identification of process uncertainties and support inverse process tracing, allowing for continuous optimization and determination of the optimal parameter combination.

Statements and Declarations

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Conflict of Interest/Competing Interests

The authors declare no conflicts of interest.

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