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Impact of semi-finished part properties and process configuration on the final geometry of structural free-form bent profiles

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Abstract. Free-form bending represents an attractive process for the manufacturing of structural components with a rectangular cross-section for the automotive industry. Due to its kinematics-based principle realized through the relative motion of the bending head with respect to a fixed holder, the process allows a high design of freedom regarding the achievable geometries. This can be of particular advantage for the realization of a profile-intensive body in white for battery electric vehicles (BEVs). On the other hand, the robustness and the sensitivity of the process for high-strength steel rectangular profiles must be evaluated in order to guarantee the strict tolerances required, which are typical for automotive manufacturing. In this contribution, the variance of the final bending results depending on the semi-finished product properties and on the bending process parameters is investigated. First, simple 2D bends were carried out in different bending planes and the effects of the process and semi-finished product properties were investigated. In addition, a small-series of a prototype geometry for a prototype C-pillar is manufactured by varying the position of the weld seam, which illustrates how much influence the semi-finished product properties have on the actual bending result.

Introduction and State of the Art

The free-form bending process with its six freely movable axes [1] makes it possible to produce components with almost unlimited geometric diversity from tubes or profiles. Another advantage is that different bending parts with the same cross-section profile can be produced without having to change the tool set [2]. This technology therefore offers considerable cost-saving potential compared to most other forming processes and could become more important for the automotive industry in the future.

Currently, the automotive industry mainly uses other forming manufacturing processes such as deep drawing [3], press hardening [4] or hydroforming [5]. However, there are considerations to use a profile-based structure in car body construction [6] and the free-form bending process with the above-mentioned advantages would be the ideal production technology for this profile-intensive car body construction method.

Nevertheless, free-form bending is a very complex process, as the bending result depends on many factors such as the semi-finished product properties. In the recent past, a great amount of research has been carried out to better understand precisely this correlation.

For example, it was investigated which residual stresses are embedded in free-form bent tubes and how these can be tailored using suitable bending strategies. By overbending and underbending,

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it is possible to vary the residual stresses within a certain range without changing the geometry of the bent tubes [2].

Another study examined how process velocities such as the feed rate, but also the moving speed of the bending head, influence the geometry of free-form bent tubes [7]. It was shown that the bending results tend to scatter more with larger bending radii. This is an observation that could be confirmed by the present work.

In other studies, the hardness and strength of weld seams in round tubes were investigated, which were subsequently free-form bent. Here it was shown which bending radius occurs depending on the deflection of the bending die [8].

However, round tubes are impractical for car body construction as they have to be milled or grinded before they can be welded to other structural components of the car body in order to ensure sufficient contact surface for a secure weld seam joint. For this reason, this investigation is repeated in a similar way in this work for squared profiles.

Experimental Setup

The bending tests were carried out on a 6-axis *NSB090-S* free-form bending machine from *Jörg Neu GmbH*, whereby 2 mm thick 40x40 mm steel profiles were bent. These are welded profiles, with the weld seam always slightly off-center on one side of the profiles. The profiles were of hot-rolled XPF800 steel. The selected feed rate was 50 mm/s for all free-form bending tests. A hand-guided *T-SCAN* laser scanner as well as the *T-TRACK 10* optical tracking system from *ZEISS* were used to digitalize the bent profiles. The subsequent quantitative determination of the radius and angle of the bent profile sections was carried out using the *GOM Inspect* software.

Experimental Plan

This study is divided into three parts. The first section of the publication examines the extent to which the process configuration influences the bending result. The main focus here is on the bending direction, which allows conclusions to be drawn about the stiffness of the bending machine in different directions.

The second part examines the effect of the semi-finished product properties of the profiles on the bending process with regard to the resulting bending angles and bending radii. The focus here is on the prevailing stress state in the weld seam.

In the final section of this work, a complex test component is bent several times while the position of the weld seam is varied. This is intended to illustrate how strongly the final geometry of free-form bent components depends on the semi-finished product properties.

Impact of the Process Configuration

In order to determine the influence of the process configuration on the bending process, 2D bendings were performed in different spatial directions. As shown in Fig. 1, bends were performed in vertical direction (P90), horizontal direction (P180) and in diagonal direction (P135).

In order to ensure that the semi-finished product properties had no influence on the bending result in this investigation, care was taken when loading the bending machine to ensure that the weld seam of the profiles was always in the neutral axis (NA) relative to the bending direction. Only for the diagonal bend this was not possible due to the non-rotationally symmetrical cross-section of the semi-finished products and here the weld seam tended to be on the tensile side of the bend.

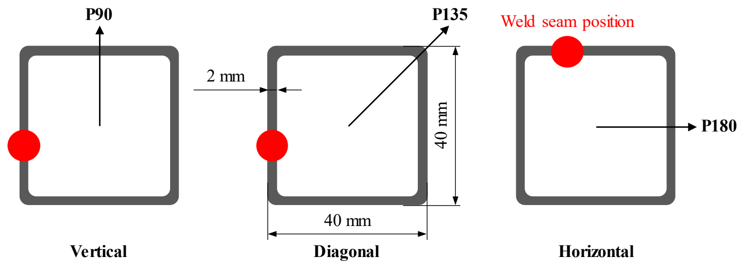

Figure 1 – Schematic illustration of the investigated bending directions with respect to the weld seam position in order to determine the influence of the process configuration on the bending result.

In this study mild (large radii), medium (medium radii) and severe (small radii) bends were investigated. In this particular examination, the severe bend radius is about nine times the profile cross-section diameter, the medium bend is approximately 15 times the profile cross-section diameter and the mild bend is approximately 20 times the profile cross-section diameter. The exact resulting radii of the individual bends can be seen in Fig. 2, and the corresponding angles of the bending sections after springback are shown in Fig. 3.

Each bar represents the results of three valid bending tests. With regard to the radius, it was shown for the mild bends that there is de facto no difference between the vertical P90 bend and the horizontal P180 bend with a bending radius of 755 mm and 753 mm respectively. The angles are also almost identical at 37.1° and 37.3° respectively. Only the diagonal P135 bend produced a larger radius of 810 mm and a slightly smaller angle of 34.4°.

For the medium bends, the values for the radii and the angles continue to further converge for the different bending directions.

The smallest differences in value were found for the severe bends. Here the average radii were 365 mm in P90, 365 mm in P135 and 352 mm in P180. All other values for radii and angles not mentioned of this test series can be seen in Table 1.

When looking at Fig. 2 and Fig. 3, it is noticeable that the largest percentage deviations between the different bending directions for both the radii and the angles are for the mild bends. The smaller the bending radii, i.e. the more severe the bend, the more the results converge. It can therefore be observed that the material is more plasticized with increasingly smaller radii, which results in smaller fluctuations in terms of bending radius and angle. The higher degree of deformation at tight bending radii reduces the impact of fluctuations in the material properties contained in the semi-finished products and contributes to a more stable bending result.

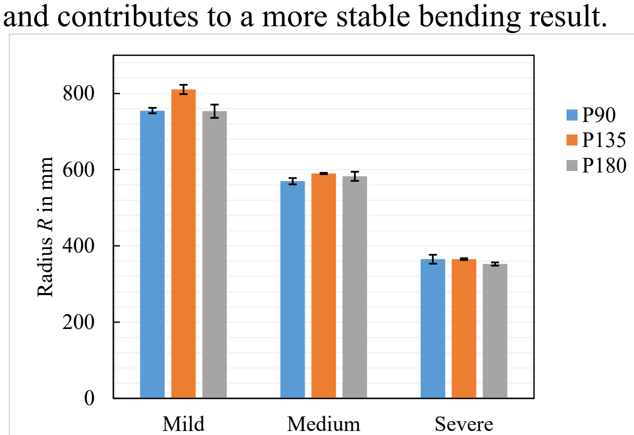

Figure 2 – Resulting bending radii depending on the bending direction for mild, medium and severe bends.

In contrast, the results in the P90 and P180 directions for the mild bend are also very similar, whereas there are larger differences in the P135 direction. As the profiles were rotated by 90° for the bends in P180 compared to the bends in P90, the weld seam runs along the neutral axis of the bend for both bends, resulting in identical stress states. It is therefore reasonable to assume that the bending machine has similar stiffness values in both the horizontal and vertical direction and that the deviation in the P135 direction is due to the fact that the weld seam tends to be on the tensile side of the bend.

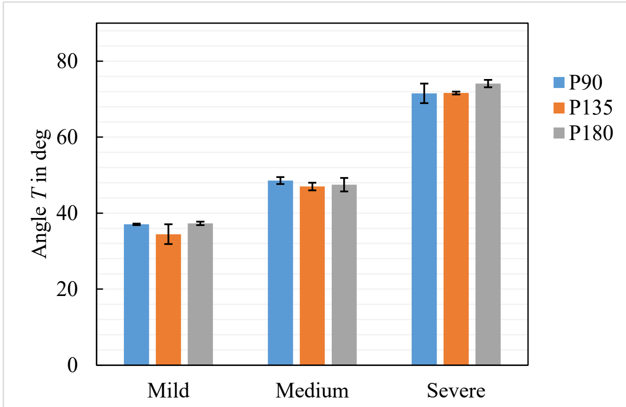

Figure 3 – Resulting bending angles depending on the bending direction for mild, medium and severe bends.

In summary, it can therefore be observed that the fluctuations in the bending result decrease with smaller bending radii due to increasing plasticization of the material and that the bending machine can be regarded as ideally stiff in every direction. In order to be able to estimate the influence of the semi-finished product properties and in particular the influence of the weld seam on the bending result, a second series of tests was carried out, which is presented in the following chapter.

Table 1 – Exact data for the resulting bending radii and angles for the first test series.

	Bending direction	Radius R in mm	Angle T in deg
Mild	P90	754.9	37.1
	P135	810.3	34.4
	P180	753.4	37.3
Medium	P90	569.9	48.6
	P135	589.9	47.0
	P180	582.6	47.5
Severe	P90	365.4	71.5
	P135	365.3	71.6
	P180	352.7	74.1

Impact of the Semi-Finished Product Properties

In order to be able to separately determine the influence of the weld seam on the bending result, further bending tests were carried out as described in Fig. 4. The profiles were always bent in the P90 direction, but the semi-finished products were always loaded into the bending machine in such a way that the weld seam was either directly on the tension side, the compression side or near to the neutral bending axis. Also in this test series, three valid bending tests were used for further evaluation.

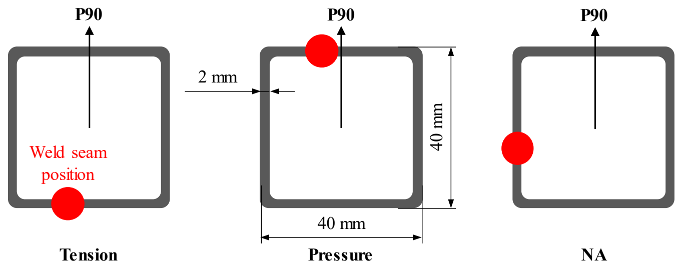

Figure 4 – Schematic illustration of the weld seam positions of the profiles during the bends in order to determine the influence of the semi-finished product properties on the bending result.

The evaluated bending radii are shown in Fig. 5. This time a clear tendency is recognizable. For all bends (mild, medium and severe), the smallest bending radii result when the weld seam is on the neutral bending axis. Interestingly, larger bending radii occur when the weld seam is on the tension side or the compression side of the bend. However, the largest radii always occur when the weld seam is on the tension side of the bend.

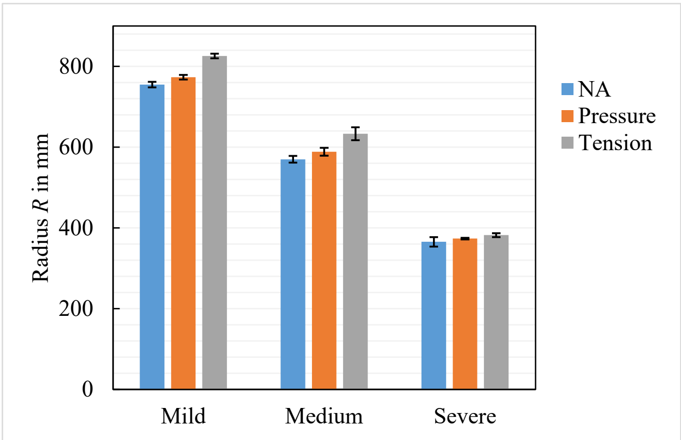

Figure 5 – Resulting bending radii depending on the prevailing stress state in the weld seam for mild, medium and severe bends.

The corresponding angles of the bent profile sections are represented in Fig. 6. Since the radius and angle cannot be changed independently of each other for a given arc line, the same trend can also be observed here. Therefore, small radii lead to larger bending angles.

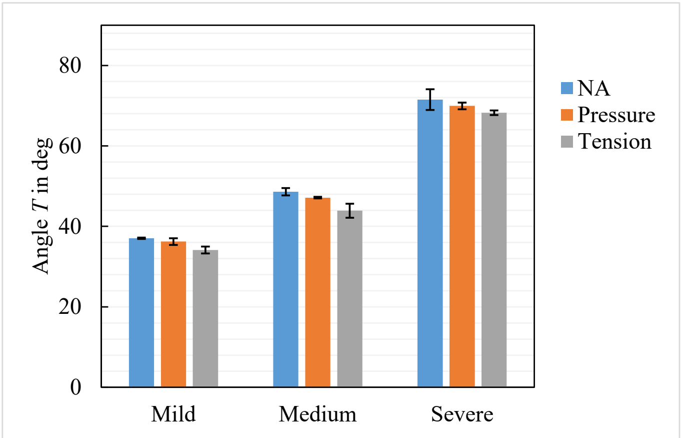

Figure 6 – Resulting bending angles depending on the prevailing stress state in the weld seam for mild, medium and severe bends.

The nominal results of this investigation with regard to radius and bending angle are summarized in Table 2.

The question remains as to why weld seams in tension/compression areas lead to larger radii or smaller angles when bending welded profiles. The tensile strength of welded joints could provide a possible explanation. Previous studies have shown that weld seams have a significantly higher tensile strength compared to the base material [8]. This would mean that when the material is formed, the yield strength is first reached in the base material and only then in the weld seam. In total, the side with the weld seam has a higher strength and therefore a higher overall yield strength than the other sides.

If the weld seam is now on the tensile side of the bend, the higher yield strength leads to greater elastic and smaller plastic deformation. In this case, the profile tends to spring back more, resulting in larger remaining bending radii.

The same relationship applies if the weld seam is on the compression side of the bend. However, the increase in compressive strength due to the weld seam appears to be lower than the increase in tensile strength. For this reason, smaller bending radii are created than in the case described above, but still larger bending radii than if the weld seam were located on the neutral axis of the bend. If, on the other hand, the weld seam is located on the neutral bending axis, the increase in strength has no effect on the remaining bending radius, as this section of the profile does not undergo any elongation anyway.

Table 2 – Exact data for the resulting bending radii and angles for the second test series.

	Bending direction	Radius *R* in mm	Angle *T* in deg
Mild	NA	754.9	37.1
	Pressure	773.1	36.2
	Tension	825.7	34.1
Medium	NA	569.9	48.6
	Pressure	588.7	47.2
	Tension	633.1	43.9
Severe	NA	365.4	71.5
	Pressure	373.4	69.9
	Tension	382.1	68.3

Prototype C-pillar as a Real Structural Component

In the last section of this work, a prototype component is used to investigate the extent to which the fluctuations in the semi-finished product properties affect the bending result of a free-form bent part. For this purpose, a prototype profile component derived from the real C-pillar of the *ID.4* from *Volkswagen AG* with a cross-section of 40x40 mm was redesigned and then free-form bent. The slightly off-center weld seam made it possible to insert the squared profiles into the bending machine in eight different ways (see Fig. 7). The component was then bent three times for each case and digitized, resulting in a data set of 24 components.

The digitized components were then aligned at one end using the best-fit method and the geometric deviations at the other end of the component are evaluated. The 40x40 mm end cross-sections vary within a range of 100x90 mm. Fig. 8 shows in detail how the end cross-sections vary in the area according to the weld seam position. It can be observed that the bending results scatter slightly even if the weld seam position is the same.

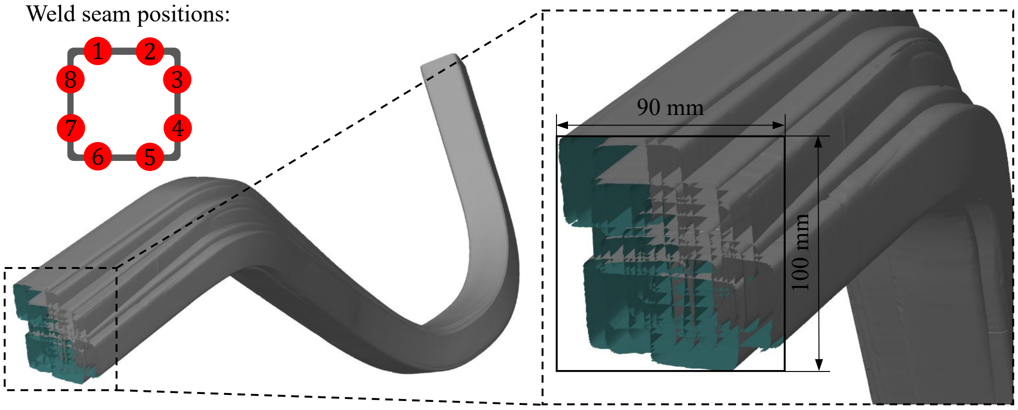

Figure 7 – Investigation of 24 bent C-pillars with same bending parameters, but with a variation of the weld seam position.

This component is a large and very complex structural component with several three-dimensional bends. And the deviation from the nominal geometry of each individual bend adds up, resulting in an overall deviation from the nominal geometry that is very difficult to control stochastically. Assuming that this structural component has to be connected to the car body at both ends, these geometric deviations caused by the fluctuating semi-finished product properties will lead to problems. For this reason, free-form bent components are typically brought into their final contour by a downstream process such as hydroforming, whereby the tolerances required for automotive construction can be maintained [9]. Nevertheless, research is currently being carried out into systems with which the free-form bending process can be monitored inline [10] and, if necessary, can react flexibly to fluctuating semi-finished product properties in order to achieve a consistently accurate bending result.

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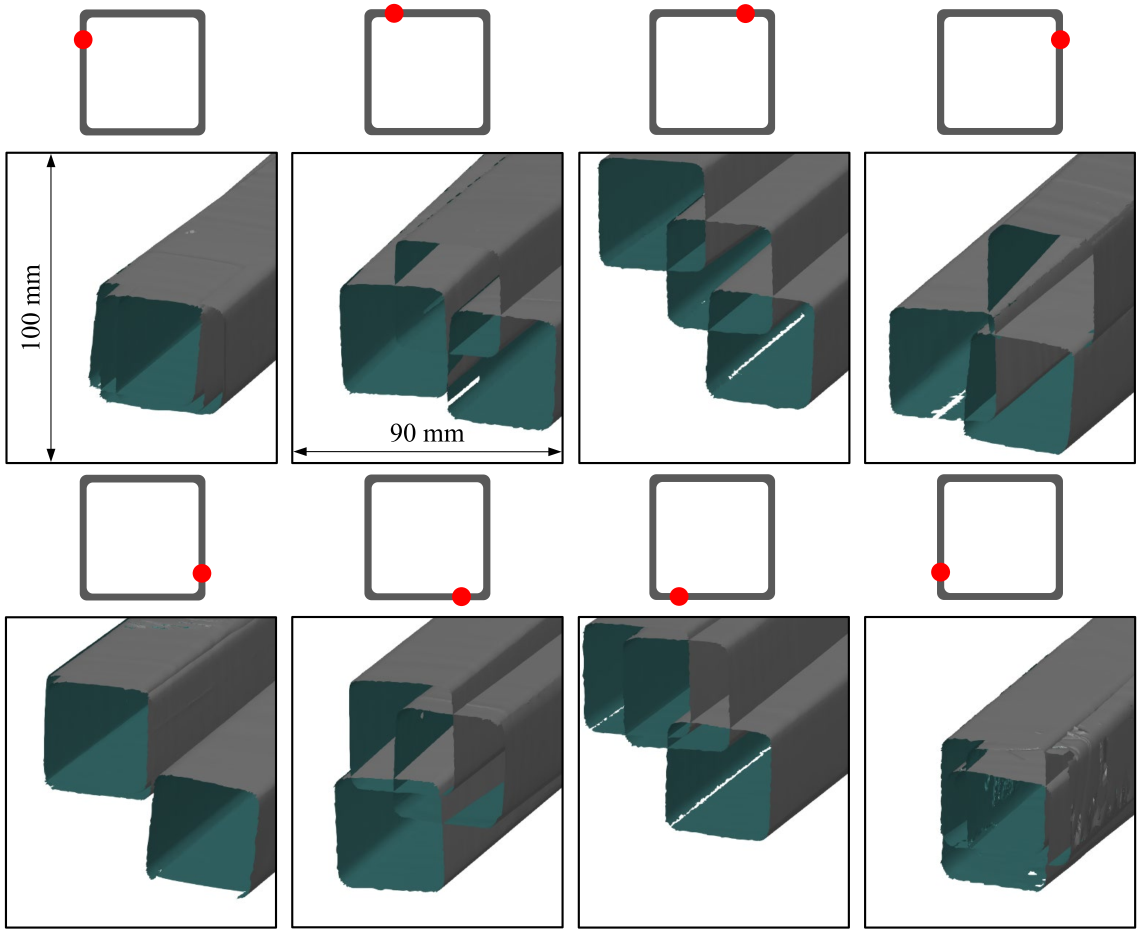

Figure 8 – Visualization of the geometric deviation of the profile end sections depending on the weld seam position during the bending process.

Conclusion and Outlook

This work investigates how the process configuration influences the bending result during free-form bending of profiles. In addition to the process configuration, special focus is also placed on the influence of semi-finished product-specific material properties such as the weld seam. The most important findings are as follows:

- The influence of the process configuration, such as the bending direction and the associated rigidity of the bending machine in different spatial directions, is rather small. This means that the bending machine is sufficiently rigid to bend the tested profiles in different directions while maintaining the same bending result.
- The semi-finished product properties of the profiles themselves and in particular the position of the weld seam during the bending process were identified as a much greater influencing factor on the bending result. Here it could be shown that the smallest bending radii occur when the weld seam is located on the neutral bending axis and that the bending radii increase when the weld seam is located in compression areas or, in particular, in tensile areas.
- The more severe the bending, i.e. the higher the degree of deformation, the less strongly any fluctuations in the semi-finished product properties affect the bending result.
- With large components, even small radius and angle errors can lead to large geometric deviations from the target geometry. Furthermore, for components with several bends, the errors of each individual bend accumulate.

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By using an actual structural component, this work demonstrates the sensitivity of the free-form bending process to fluctuating semi-finished product properties and uses simple 2D bends to illustrate how the weld seam influences the bending result. This practical investigation is intended to demonstrate that there is a compelling need to monitor the free-form bending process inline, to detect developing geometric deviations from the target geometry at an early stage and to take appropriate countermeasures so that the tolerances required for automotive construction can be maintained. Research is currently being carried out on this control system for free-form bending processes and progress will soon be presented in further publications.

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