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Influencing geometric stability in free-form bending by exploiting non-tangential bending

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Abstract. Free-form bending is a kinematics-based bending process, which offers a wide flexibility for bending arbitrary 3D-geometries. Especially in the automotive sector, it can represent an optimal process for the bending of structural components in high strength materials from the prototyping up to the series production, due to the reduction of tooling costs and the ease of process adjustment. Nevertheless, it still requires a complex design of the kinematics of the bending die in order to obtain the part in the desired tolerance range. In this contribution, the effect of different kinematic strategies on the geometrical stability of the process is investigated. First, the principles of tangential and non-tangential bending (under- and overbending) are described. Successively, the strategies are tested on different semi-finished parts before and after different heat treatments to simulate inhomogenities in the materials. Finally, the results are discussed, and it is found, that the overbending strategy allows to reduce the fluctuations in the obtained bending radius and angle, hence improving the stability and reproducibility of the process.

Introduction

The increasing demand in the automotive industry for lightweight structures and high-strength materials leads to the design of always more complex geometries, that must undergo series production in a robust and efficient way. In this scenario free-form bending is gaining popularity, as it allows to manufacture virtually any 3D-shape with the use of a single tool. Its flexibility and moderate costs make it attractive, especially in the automotive industry, for the realisation of complex structural parts made of circular or rectangular profiles. As a kinematics-based process, it also has many degrees of freedom to compensate for possible deviations from the nominal geometry. This can occur due to the batch fluctuations in the material of the semi-finished part and can lead to the rejection of the part. Nevertheless, if detected through material testing before bending, batch fluctuations could be compensated for by adapting the kinematics of the bending die. Maier et al. [1] introduce the non-tangential bending and demonstrated that the same geometry can be produced with different kinematics, inducing different residual stress states. This is an intrinsic property of the process and can be exploited to enhance its robustness. The aim of this work is to show the effect of different bending strategies on the reproducibility of the bent results. First of all, a review of the most common and established bending processes for structural parts with particular focus on free-form bending is proposed. Successively, the theoretical framework of the tangential and non-tangential bending is explained, showing the principles for enhancing the robustness of the process.

Finally, a validation based on experimental results is carried out. Semi-finished tubes from the same batch are heat-treated following different cooling paths to simulate different batches and induce unequal residual stress states. The results show that the robustness of the process can be influenced by the adaption of the bending die kinematics, hence making an additional step towards the industrialisation of the free-form bending process. The aim of this work is to show, that the overbending strategy leads to a more robust process compared to the tangentially bent tubes and that underbending results in a wider range of the desired geometry.

State of the art

The spectrum of existing bending processes offers different possibilities for the manufacturing of structural components made from high strength materials [2]. The most common bending processes for tubular components is rotary-draw bending [3]. The process is very suitable for the realisation of small bending ratios BR (1.5 < bending radius/tube outer diameter < 2.5) and large wall thickness ratios (tube diameter/tube wall thickness ≥ 30) [4]. This is made possible with reduced wrinkles and cross-section deformations thanks to the fixed contact between part and the mandrel [5]. Nevertheless, consecutive bents cannot be realised without segments of linear transitions due to the clamping of the tools. In addition, although different bending angles and planes can be achieved with the same setup, the bending radius is directly defined by the tools, limiting the flexibility of the process. Another common possibility is represented by thre-roll push bending [6]. The process allows for extremely small radii (BR < 2), but still can realise only fixed radii defined by the geometry of the rolls [7]. In this context, free-form bending can be the process of choice for a wide range of possible target geometries and materials, thanks to its outstanding flexibility and modularity [8]. The working principle of free-form bending has been firstly proposed by Murata [9], who developed the MOS bending process. Another version of the free-form bending process has been realised at the Fraunhofer IWU Institute with the Hexabend machine [10]. The plant is based on a stiff structure called Hexapod, made of four actuators equipped with Cardan joints. The Torque Superposed Spatial (TSS) bending can be also considered a free-form bending machine and realizes the torque degree of freedom through a torsion bearing axis, while the feed is achieved with rolls [11]. Finally, the free-form bending process can be realized with different degrees of freedom and bending tools, such as the spherical joint investigated by Gantner [8], or the 6-degrees-of-freedom (DOFs) plant offered by J. Neu GmbH [12]. This is the machine available at the Chair of Metal Forming and Casting, on which all the experimental tests have been carried out. In the following section, the principles of tangential and non-tangential bending (under- and overbending) are described.

Strategy

Free-form bending with a movable die is realised through the relative movement of the bending die with respect to the fixed holder at a constant feed rate. The derivation of the kinematics of the die in order to realize the required radius is not a trivial task and represents an inverse problem. On a single bending plane, the bending die kinematics is constituted by 2 DOFs, namely its deflection u and rotation a. Typically, the machine is calibrated through experimental results, generating an experimental correlation between the first DOF, the deflection u and the resulting bending radius R. The second DOF, the rotation a, is not included explicitly in the calibration process and is a dependent variable of the deflection. The rotation of the tool is adjusted depending on the desired deflection, so that the bending die remains tangential to the bent component. This represents the standard configuration for free-form bending and its denoted as *tangential bending*. Nevertheless, it is possible to adjust the rotation of the die arbitrarily and independently of the deflection through the feeding of an NC-programme. This makes it possible to use the second DOF completely and to develop different strategies, whereby, for example, a non-tangential position of the bending die can also be achieved. If the imposed rotation is less than the tangential rotation, the *underbending* strategy is employed. If the rotation is greater than the tangential rotation, the *overbending* strategy is employed. The 3 described strategies are summarized in \cref{table:1} and graphically depicted in Fig. 1.

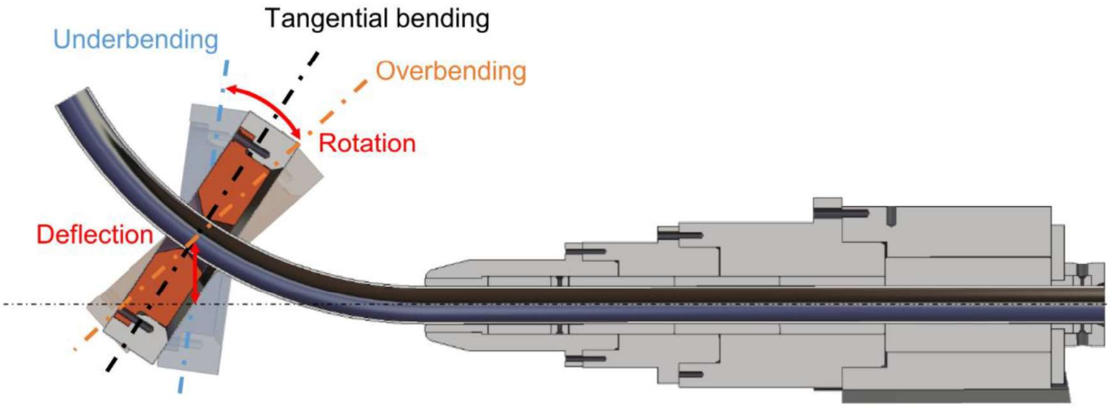


Fig. 1: Schematic depiction of tangential, under- and overbending

Previous studies have shown that different couples of deflection-rotation can lead to the same bending radius, yet with different stress states [1]. This indicates that the bending strategy has a clear impact on the bending result and can be employed to improve the geometric stability of the process and reduce its sensitiveness to batch fluctuations. In this context, the overbending strategy should smear the fluctuations in the resulting radius, as it induces a higher loading on the material. In addition to the global bending solicitation, an additional local bending contributes to the forming of the curvature. In contrast, the underbending is expected to deliver higher fluctuations, as the local bending solicitation counteracts to some extent the global loading. In the following section, experimental tests are carried out to verify the assumptions of the authors. In order to dispose of raw materials in different initial states, to simulate the occurring of batch fluctuations or residual stresses effects, 2 heat treatments are carried out. Successively, the 3 kinematic strategies are tested on all the semi-finished parts, as described in the following section.

Tab.1: Tangential and non-tangential bending strategies

Kinematic	Underbending	Tangential bending	Overbending
Rotation in deg	$a < a_T$	$a = a_T$	$a > a_T$

Experimental investigations

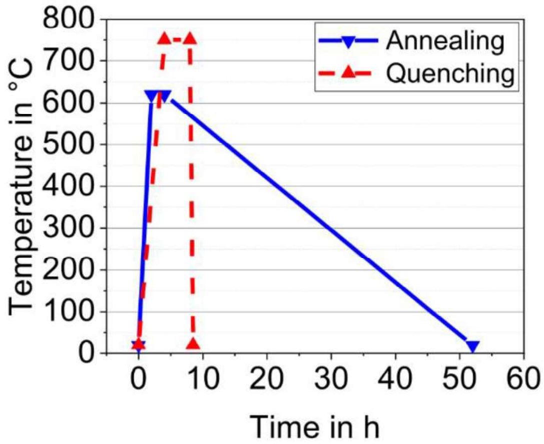
For the experimental tests 3 different states (stress relieved, normalized and quenched) of the steel tube are considered. For each state 3 different bending strategies (underbending, tangential bending and overbending) with 4 experiments each are investigated. This makes a total of 36 bending experiments. For evaluation, the resulting angle between the two legs and the radius in the constantly bent area are measured for each bent tube and then analyzed.

Heat treatment

To get different mechanical properties within the steel tubes, the normal steel tubes are heat treated. On the one hand, the residual stresses of a batch of tubes are minimized by residual stress annealing. The concept of stress annealing for the tubes used in this work has already been shown in [1]. The steel tubes are heated up to $620\,°C$ within $2\,h$, then held at this temperature for another $2\,h$ and are afterwards cooled down to room temperature in $48\,h$. The annealing was performed in a chamber furnace in an air environment and the tubes were placed in the center to guarantee comparable heating all around the tubes.

On the other hand, the normal steel tubes are heated and quenched in order to generate differences in the mechanical properties and respectively residual stresses within the length of the tubes. For this purpose, the tubes are heated up to the maximum temperature of the furnance

($750\,°C$) and held at this temperature for $2\,h$. This ensures that the tubes are heated homogeneously. The tubes are then removed from the furnace and quenched directly in room-temperature water. In Fig. 2 (left) the ideal temperature curve over the times for the stress annealing and the quenching of the steel tubes is depicted. Fig. 2 (right) shows a picture of all tubes in the furnace after they were heated up to the maximum temperature.



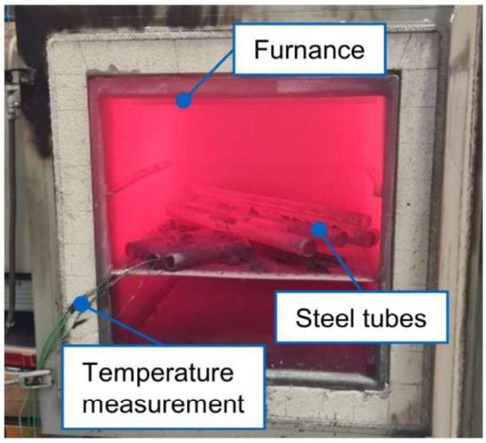


Fig. 2: Time-Temperature diagram for stress annealing and quenching and picture of heat treatment of semi-finished parts

Free-form bending

In order to show a clear difference between tangential and non-tangential bending, the tubes were previously subjected to different heat treatment processes. For the experimental investigations, 5 tubes from each heat treatment strategy are free-form bent using the same kinematics. This results in 15 free-form bent tubes per selected bending kinematics (underbending, tangential bending and overbending). The kinematics have the same deflection value, but differ in the rotation of the bending die (see Tab. 2).

Tab. 2: Kinematics of the bending die for underbending, tangential bending and overbending

Kinematic	Underbending	Tangential bending	Overbending
Deflection in mm	10	10	10
Rotation in deg	5	16	27

After the tubes have been bent the surface is measured by using a handheld laser sensor and a discrete surface of the free-form bent tube is generated. Afterwards, the tubes are analyzed according to the resulting constant radius and the bending angle. To measure the bending angle between the two legs of the free-form bent part, two cylinders are fitted at the straight ends of the tube. The bending angle is measured on the outside of the tube and between the intersecting center lines of the cylinders. For the radius the center line of the whole free-form bent tube is generated. For this purpose, the discrete surface is cut in equally spaced sections and a circle is fitted through each section. The center line is created by connecting the individual middle points of the circles. This center line is analyzed by the curvature and a circle is fitted through the constant area of the curvature. The radius of the resulting circle is called bending radius of the tube. In this procedure, the bending radius is assumed to be ideal according to [3], and process-related bending characteristics are not taken into account. The result of the bending radius and the bending angle for all investigated experiments can be seen in Fig. 3.

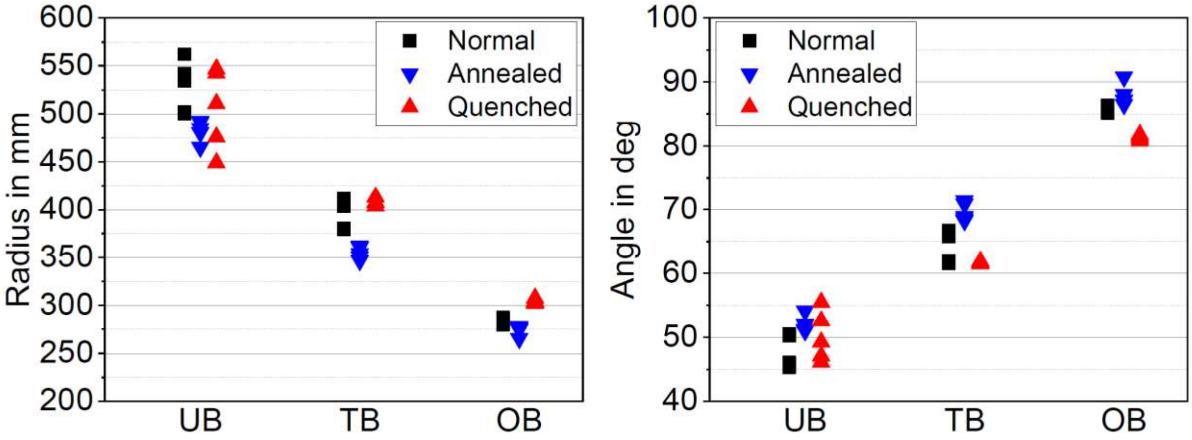


Fig. 3: Bending radius (left) and bending angle (right) for underbending (UB), tangential bending (TB) and overbending (OB) different treated steel tubes

Discussion

First of all, it is shown that the bending radius decreases with increasing rotation of the bending die for all different tube states. With decreasing bending radius, the bending angle increases due to the fact, that the length of the bending line is constant. It can also be seen that the resulting radius varies for the different conditions, even when the bending kinematics are the same. For example the radius of the annealed parts are always smaller compared to the normal parts. The inverse relationship can also be seen for the bending angles, as already mentioned, since the angles are directly related to the bent length and radius.

Fig. 3 also shows that the deviation in radius and angle of overbending is smaller compared to tangential bending and underbending. This can be seen for all steel tube conditions, but most obvious within the normal tubes. As well as for the stress annealed as for the quenched tubes the deviation in tangetial bending is comparable to the deviation of overbending, but both are smaller compared to the underbending. In addition, Fig. 3 shows that the deviation of radius and angle is smaller for overbending than for tangential bending and underbending. This can be seen for all steel tube conditions but is most evident for the normal tubes. Furthermore, the distribution of results for both the annealed and quenched tubes in tangential bending is comparable to the deviation in overbending. For both conditions, the largest deviation in results continues to be seen for the underbent tubes.

The experimental results show that the rotation of the bending die has an impact on the resulting geometry, especially on the radius and the angle of the free-form bent tube. The results in Fig. 3 also confirm the theory of this work, that overbending the tubes lead to more geometrical stability compared to tangential bending or underbending of the tubes. This can be seen in a smaller deviation of the resulting bending radius and angle.

During overbending, the die is rotated further than during tangential bending, while the deflection remains constant (see Fig. 1). As a result, the point of application of the force is shifted further forward and at the same time further upward, which in principle corresponds to a minimally larger deflection. In addition, the new position changes the clearance between the tube and die, which becomes smaller or also negative with increasing rotation. Due to the decreasing clearance between die and tube, fluctuations in the starting material (e.g. cross-section or residual stresses) are absorbed much better or undergo more forming and thus have less effect on the overall geometry of the free-form bent part.

The reverse case is represented by underbending, since the clearance between tube and die is greater than in comparison with tangential bending and overbending. As a result, the fluctuations in the base material are less absorbed and have a greater effect on the overall component.

This knowledge is further supported by the results in Tab. 3, as this also explains the less pronounced deviations in TB for annealed and quenched tubes. As can be seen, the outer diameter is larger for the heat treated tubes than for the normal tubes. Due to this expansion of the tubes, there is already a smaller clearance between the deflected bending die and the tube during tangential bending, which means that the tubes are more influenced and, in the course of this, also exhibit less variation in radius and geometry.

Tab. 3: Outer diameter of the semi-finished tubes before and after heat treatment

[mm]	Mean value	Maximum	Minimum	Roundness
Normal	42.63	42.75	42.54	0.12
Quenched	42.43	42.96	42.07	0.56
Annealed	42.56	42.23	42.98	0.34

Conclusion and Outlook

This work presented the influences of non-tangential bending compared to tangential bending in terms of geometrical stability of free-form bending. For this purpose, various heat-treated tubes were free-form bent using bending strategies, with the bending die either tangential to the tube or with more or less rotation (overbending and underbending). The results can be summarized as follows:

- Heat treatment of steel tubes leads to deviations in radius and angle compared to free-form bent steel tubes without heat treatment
- Non-tangential bending strategies can result in either more (underbending) or less (overbending) deviations in part geometry depending on the rotation of the bending die
- Maintaining the deflection of the bending die while increasing the rotation (overbending) results in more geometric stability and robustness against batch fluctuations, as the clearance between the bending die and the tube is smaller and the tube is bent more precisely

All together this work shows that the rotation of the bending die can be used to influence the geometry of the free-form bent part. This result can be used to create a geometry based closed-loop control for free-form bending with a movable die. In the future, the influence of bending die rotation needs to be studied in more detail, as well as the effects on different materials and cross sections.

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