A study on springback of bending linear flow split profiles

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Abstract. The bending of linear flow split profiles made up of high strength materials involves high bending loads leading to high springback and geometrical defects. In addition, the linear flow split profiles are made stronger due to the high plastic deformation applied by the process itself. The bending method proposed in this paper combines the linear flow splitting process with a movable bending tool. The aim of the research was to investigate the effect of superimposed stresses exerted by the linear flow splitting process on bending load and springback of the profile by using a finite element model. The latter was validated by means of experimental results. The results show that the bending loads and the springback were reduced by increasing the superposition of stress applied by the linear flow splitting process. The reduction in the bending loads leads to a reduction in the cross-sectional distortion. Furthermore, the springback was compensated by controlling the amount of superimposed stress.

1. Introduction
Springback is a change in shape of a metal sheet after forming due to its elastic recovery. It is inevitable and causes shape discrepancies in the final product. In recent years, research on springback has grown considerably. Due to the demand on weight reduction mainly in the automotive sector, the application of high-strength materials has increased significantly. High springback, associated with high-strength materials, makes the study of prediction and compensation of springback a challenging task [1].

Several studies were undertaken to reduce springback in bending sheet metal. Bending high-strength steel under warm conditions reduces or even eliminates springback [2] [3]. One of the promising techniques to reduce springback is to superimpose stresses in the bending zone. The Stretch forming applies additional axial tension in the bending zone resulting in the reduction of springback. This axial tension can be controlled to reduce springback [4]. Another example of uniaxial superimposed stress is found in air bending. In this process, springback reduction of 60% was found when stresses were superimposed in the thickness direction [5]. The Torque Superposed Spatial (TSS) bending process superimposes torsional stresses to the bending moment. These stresses reduce bending forces, cross-sectional distortion and springback [6]. The incremental tube forming process which combines tube spinning and bending operations applies multidimensional stresses resulting from the reduction in the diameter of the tube. This process shows a significant reduction in bending moment and springback [7].

The linear flow splitting process is a multi-station sheet-bulk metal forming process which allows continuous production of bifurcated profiles. This process is often carried out on high-strength
materials. Therefore, bending of linear flow split profiles is one of the most challenging tasks due to high springback.

Bending linear flow split profiles remains a challenge because of the requirement of mass production, flexibility and the use of high strength materials. In this paper, the process of bending linear flow split profiles is presented. A bending tool system is used to bend the profiles in a continuous manner. This tool system considers the aforementioned procedure of stress superposition in the bending zone. The aim of this paper is to analyze the effect of stress superposition on the reduction of bending forces and springback. A numerical model of the whole process is developed to investigate the effects of stress superposition on bending forces and springback. The model is verified with the help of experimental results for the bending force and the springback ratio. Furthermore, the model shows the effect of variation of superimposed stresses on the bending force and the springback ratio.

2. Linear Flow splitting
Linear flow splitting is a multi-station process which forms a metal sheet into a bifurcated profile at room temperature. The bifurcation of the metal sheet into flanges is made possible by a pair of obtuse angled supporting rolls and splitting rolls at each station, as shown in figure 1. The metal sheet is moved by means of rotating supporting rolls. At each station \( n \), the splitting rolls are closed in by an incremental depth \( y_{inc} \). The width of the supporting rolls is also reduced accordingly. Therefore, the surface area of the metal sheet edge is increased at each station. The process is continued until the desired geometry is achieved [8].

![Linear flow splitting](image)

**Figure 1.** Principle of the linear flow splitting process

In the forming zone, splitting rolls exert high compressive stresses in transverse direction which allows the formation of flanges. However, some amount of the plastified material flows in the thickness direction. This thicker part of the web is rolled by the supporting rolls. The combination of these two deformation mechanisms allows high hydrostatic stresses in the forming zone. High hydrostatic stresses are beneficial in elevating formability of the sheet metal in the forming zone. Thus, the linear flow splitting process applies multi-axial stresses in the forming zone [9].
3. Experimental setup

The experimental setup consists of a decoiler, seven stations of the linear flow splitting process, a tool system for the bending operation and a profile cutting machine. A high-strength steel “RAWAEL 80” (Yield strength = 840 MPa) is used in all investigations. The tool system for the bending operation consists of a bending roll, a calibrated load cell and a blankholder mounted on a rotary table, as shown in figure 2 (a).

![Figure 2. Bending process](image)

In all investigations, the linear flow split profile is bent in transverse direction only. Due to the stress superposition by the linear flow splitting process in the forming zone, bending forces exerted on the tool system are expected to be lower than the forming forces. Therefore, the diameter of the bending roller is kept smaller than the splitting roller. The tool system for the bending operation is positioned directly after the last linear flow splitting station on the same height as the splitting rollers which allows a continuous production, as shown in figure 2 (b). The distances between the bending roller from the splitting rollers of the last station \( X \) and \( Y \) determine the bending radius \( R_t \). The values of \( X \) and \( Y \) as well as the process parameters chosen for the experiments are given in table 1 (a) and (b).

| \( X \) (mm) | \( Y \) (mm) | \( R_t \) (mm) | Process Parameter | Value |
|----------|----------|----------------|-------------------|-------|
| 425.36   | 100      | 600            | Velocity of the metal sheet, \( V_{\text{sheet}} \) | 3 m/min |
| 546.01   | 100      | 1000           | Initial sheet width, \( b_{\text{initial}} \) | 50 mm |
| 644.46   | 100      | 1400           | Width of the profile before bending, \( b_{n-1} \) | 35.5 mm, 34.5 mm |
| 729.74   | 100      | 1800           | Incremental depth at the last station, \( y_{\text{inc}} \) | 1.5 mm, 2 mm |
| 806.06   | 100      | 2200           | Total incremental depth, \( y_{\text{inc, total}} \) | 9.5 mm |

Therefore, widths of the profiles before the last linear flow splitting station are considered as 34.5 mm and 35.5 mm for incremental depths of 1.5 mm and 2 mm respectively. Therefore, the width of the
The profile in the FE model is symmetric in thickness direction, as shown in figure 3. Initial material data was obtained from tensile tests to calculate the yield stress and the strain hardening coefficient. The material data for flanges and web is derived from experimental hardness measurements and fitted in Ludwik’s equations $k_{f,\text{flange}} = 1250 \varepsilon^{0.02}$ and $k_{f,\text{web}} = 951 \varepsilon^{0.02}$. As a characteristic of the linear flow splitting process, flanges possess a higher strength than the material in the web because of high forming strains [9]. The Von mises yield criterion is considered with the isotropic hardening rule. All rollers are defined as analytical rigid bodies because of their high stiffness. The model is simulated using a Coulomb friction coefficient of 0.12 between rollers and the sheet. The model uses 8-noded hex elements with an assumed strain formulation to accurately simulate the behavior under bending process. Thermal effects are neglected.

The length of the sheet is taken as 2500 mm to achieve the steady state which is often assumed in continuous forming processes. To reduce the computational time, the nodes at the end of the sheet are fixed in all three directions and the rollers move across the sheet to retain the relative motion. At the start of the analysis, the bending roller is positioned at $X$ distance from the last forming stand according to the desired bending radius $R_f$. Furthermore, the bending roller is moved in transverse and longitudinal direction until it reaches a designed position $Y$. After positioning the bending roller at $X$ and $Y$ distance from the splitting rollers, it is further moved only in longitudinal direction with the same velocity as that of the other forming rollers. All rollers are moved away from the profile at the end of the simulation. A python script measures the coordinate data from the nodes located at the
middle of the bent profile. This data is curve fitted in Matlab to find the bending radius after the springback \( R_3 \).

5. Results and discussion

5.1. Verification of the numerical model

5.1.1. Bending force

The verification of the numerical model was carried out by comparing bending forces measured in the experiments and in the simulations for incremental depths of 1.5 mm and 2 mm, as shown in figure 4.

![Figure 4. Verification of the numerical model](image)

The bending forces predicted by the numerical model confirm the forces measured in the experiments for both incremental depths \( y_{inc} = 1.5 \) mm and \( y_{inc} = 2 \) mm. In addition, it can be observed that bending forces decrease with increasing the bending radii. The stress superimposed in the last forming stand increases with the increased incremental depth \( y_{inc} \). Therefore, bending forces exerted for \( y_{inc} = 2 \) mm are less than for \( y_{inc} = 1.5 \) mm for all bending radii considered. It is interesting to note that the magnitude of the bending force is very small because the bending zone is already plastified in the last linear flow splitting station.

5.1.2. Springback ratio \( K \)

The springback ratio \( K \) is defined as the ratio of the radius before springback \( R_1 \) to the radius after springback \( R_2 \).

\[
K = \frac{R_1}{R_2}
\] (1)
The influence of the incremental depth on the normal ratio. To understand the amount of stress superimposed during the linear flow splitting process, the stress superposition in this bending process can be controlled by adjusting the incremental depth in the bending radius for both incremental depths. Besides, at higher incremental depth of 2 mm, the springback ratio was higher for every bending radius compared to the incremental depth of 1.5 mm. This suggests that with higher incremental depths, the amount of springback decreases.

5.2. Effect of stress superposition
Stress superposition plays an important role in the reduction of the bending force and the springback ratio. To understand the amount of stress superimposed during the linear flow splitting process, the normal stresses along the width of the profile are plotted, as shown in figure 6 (a). The figure shows the influence of the incremental depth on the normal stress in the forming zone. This suggests that the stress superposition in this bending process can be controlled by adjusting the incremental depth in the last forming stand.

Figure 5. Variation of springback ratio $K$ with bending radius $R_l$

Figure 6. Normal stress in (a) linear flow splitting, (b) linear flow splitting and bending process
Figure 6 (b) presents the effect of the bending operation in the stress superimposed forming zone. The normal stresses were measured at the forming zone which also describes that bending takes place within the forming zone created by the linear flow splitting process.

Variation in stress superposition affects the bending force as well as the springback ratio, as shown in figure 7 (a), (b). It can be seen clearly that the increase in the stress superposition reduces the bending force. The springback ratio decreases with decreasing the incremental depth as well.

![Figure 7](image)

**Figure 7.** Effect of stress superposition on (a) bending force, (b) springback ratio

It is interesting to note that the springback ratio increases with increasing the bending radius when the stress is superimposed in the bending zone, whereas the springback ratio shows the opposite trend in the absence of superimposed stress, as shown in figure 7 (b). At incremental depth $y_{inc} = 0$ mm, bending forces were higher with lower springback ratios. At $y_{inc} = 0.65$ mm, it was found that the springback ratio remains constant irrespective of the bending radius considered for the investigations.

6. Conclusion

The numerical model for the process was developed. The model was successfully verified with the experimental results for bending forces as well as the springback ratio. The maximum amount of error in predicting bending forces and springback ratios was found to be 0.7% and 1% respectively.

The amount of stress superimposed in the bending zone plays an important role in the reduction of bending forces and the springback ratio. Bending forces were reduced at least by 86% whereas the springback ratio was increased at least by 9.4% in the presence of superimposed stress. Furthermore, the springback ratio with the stress superposition shows little variation for the considered bending radii. In current investigations, the springback ratio remained constant for an incremental depth of 0.65 mm irrespective of the bending radii.

The results from the numerical model as well as the experiments show the effectiveness of stress superposition in the bending zone to reduce higher bending forces and springback. With this bending process, it is beneficial to bend the linear flow split profiles in a continuous manner with less springback.
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