Warping and springback reduction in bending of U-profiles through partial heating over the cross-section

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Abstract. Bending of profiles is challenging due to the high stiffness and possible deformations in the process. Especially bending of profiles with asymmetric cross-section regarding the force initiation axis leads to unwanted warping of the bent profile. This warping results from the position difference between the force initiation axis and the shear center, implying torsion moments on the profile. To prevent profile warping the use of shape-bound tools or a change of the force initiation axis position are common practices, though these methods reduce the flexibility of the process. A new method to prevent profile warping during bending is the use of partial cross-sectional heating. Due to thermal softening in one profile area a quasi-symmetric bending case is achieved, which changes the position of the stress-free fiber and thus reduces the torsion moment. In this work, the warping and springback behavior of partially heated U-profiles consisting of S500MC steel after a three-roll push bending process is investigated using experimental methods. Through partial heating of one profile area to up to 600 °C, a warping reduction of 83 % and a springback reduction of 69 % were achieved.

1. Introduction

The production of lightweight components is focused for automotive body construction due to the increasing requirements regarding CO₂ emissions. Additionally, the range of produced parts is increasing as more model variety is desired. In that sense, the use of kinematic bending processes for profiles is favorable as these are flexible and offer a broad product spectrum. Compared to form-bound bending processes, however, the geometric product accuracy for kinematic processes is reduced.

Especially the bending of asymmetric profiles regarding the force initiation axis is a problematic case due to possible warping. When applying a force central on the profile area torsion moments are initiated in the profile which lead to warping of the cross-section (Figure 1 (a)). Different methods exist to eliminate profile warping. Welded blanks can be used to move the force initiation axis in direction of the shear center (Figure 1 (b)) [1]. Through the position of the force a counter torsion moment to the geometrical torsion moment is initialized, eliminating the torsion moments in the profile. Another method is to use support elements to constrain the forming zone (Figure 1 (c)) [2]. Additionally, special processes use counteracting torsional forces to reduce this effect, like the Torque Superposed Spatial-bending (TSS) process [3]. While such methods are able to successfully negate profile warping either additional tool elements or the change of the profile geometry are necessary. Thus the flexibility of the processes is reduced. To maximize the flexibility of these bending processes while maintaining a high geometrical accuracy a new method is required.
Figure 1. (a) Profile warping due to asymmetry, (b) warping prevention through force positioning, (c) warping prevention through support elements.

The state of the art describes several methods to prevent unfavourable deformation in metal forming through partial heating. Flame straightening for example is a process that is used in ship body production [4]. After welding, large metal sheets are heated to reduce the thermal deformation implied by the bending process. The process of laser bending evolved from this method. In this process, the thermal energy of a laser is used to bend metal sheets and profiles without springback [5]. In the case of springback, Yanagimoto et al. [6] prevented springback in the v-bending of high-strength steel sheets through the use of high temperatures. The prevention of springback is explainable through the reduction of the bending moment due to thermal softening of the steel sheets.

Based on these ideas, this work aims to investigate the suitability of partial heating to reduce springback and warping in asymmetric bending of U-profiles through three-roll-push bending. The use of partial heating for the bending of L-profiles has been proven to reduce warping up to 76 % and springback up to 44 % compared to the room temperature case for the material S500MC and partial heating temperatures of up to 600 °C [7]. The resulting warping and springback data for bending with partial heating of U-profiles is compared with the data for L-profiles.

2. Bending of U-profiles with partially heated cross-section

2.1. Process principle

Warping in bending of profiles will occur if the position of the force application axis differs from the position of the shear center (Figure 2 (a) [8]. In this case, shear stresses are initiated in the profile which imply a torsion moment on the profile cross-section due to its geometry. This torsion moment implies a distortion on the profile by an angle of $\alpha$ (Figure 2 (b).

Partial heating leads to thermal softening in parts of the profile. As the thermal softening reduces the flow stress necessary to bend the profile to the same radius as in the room temperature case, the stresses, especially the shear stresses, in the cross-section are reduced. As thermal softening is not uniform in the cross-section, the position of the shear center changes. In the depicted heating case, the shear center shifts in direction of the force initiation axis, effectively reducing the torsion lever arm length for the bending process. Consequently, the torsion moment, as well as the warping angle, is decreased. This effect can be used to reduce warping in profile bending processes.
In the case of springback, the partial heating of the profile will reduce the flow stress locally through thermal softening. As the softening reduces the global stiffness of the profile a smaller bending moment is necessary to bend the desired bending radius, which leads to reduced springback [6].

### 2.2. Experimental procedure

To analyze the effect of partial, cross-sectional heating on profile springback and warping during kinematic bending, a three-roll push-bending process realized on a rotatory draw bending machine DB 2060-CNC-SE-F (transfluid, Schmallenberg, Germany) is used. The process is divided into three phases: Prebending, kinematic push-bending, and unloading. In prebending, the inner bending radius of the profile is set to 600 mm by rotation of the bending roll (Figure 3 (a)). In the kinematic push-bending phase the profile is fed with a constant feed velocity $v_f$ of 8 mm/s. In this phase, the profile is partially heated (as in Figure 2 (c) at 70 mm after the counter roll to temperatures between 200 °C and 600 °C in 100 °C steps, if the profile is not at room temperature. This temperature range is chosen to have minimal influence on the microstructure. The heating is achieved through induction by a Trumpf TruHeat 7040 induction generator with a power of 40 kW. At the position of the induction coil, the temperature is measured by a Sensortherm pyrometer M318. After passing the length of the heating zone of 95 mm the profile is cooled by a water-jet cooling system to localize the heating zone. When the desired bend length of the profile is reached, the profile is unloaded and springback will occur. The geometry after unloading is then digitalized using the 3D scanning system GOM ATOS to evaluate warping and springback.

![Figure 2](image1.png)

**Figure 2.** (a) Shear stresses due to force application, (b) resulting warping in the profile cross-section, (c) reduced shear stresses through partial, cross-sectional heating

The heating zone and the cooling zone have been divided by a plate consisting of the material Dotherm, which does not influence the inductive heating but prevents the water spray to reach the heating zone (Figure 4 (a)). The tooling in the forming zone consists of the guide, counter, and bending roll, the pyrometer, the induction coil, the cooling jet, and the divider sheet (Figure 4 (b)).
2.3. Material
The investigated U-profiles are 2000 mm long with a length of the outer edges of 40 mm with a thickness of 1.5 mm and 2.5 mm. These profiles consist of S500MC steel. Delivery conditions of the material are according to EN 10140-2 (Table 1).

| Yield strength $R_{p0.2}$ in MPa | Tensile strength $R_m$ in MPa | Chemical composition in wt% |
|----------------------------------|--------------------------------|-----------------------------|
| 585                              | 642                            | C  | Si    | Mn | P   | S   | Al  | Nb  | Ti  | V   |
|                                  |                                | 0.045 | 0.02  | 0.812 | 0.013 | 0.007 | 0.032 | 0.013 | 0.001 | 0.137 |

Additionally, temperature-dependent Young’s moduli (Figure 5 (a) and temperature and strain rate dependent flow curves (Figure 5 (b) were obtained through isothermal tensile tests on 2.5 mm thick sheet specimens. The tests were carried out on a Zwick Z250 tensile testing machine and the sheets were heated through induction. The investigated temperatures range from 25 °C to 600 °C in 100 °C steps and the analyzed strain rates are 0.0003 1/s, 0.003 1/s, 0.03 1/s and 0.1 1/s.

![Figure 4. Process set up. (a) process frontal direction, (b) close up of the tools in the forming zone](image)

![Figure 5. Material properties. (a) Young’s moduli, (b) flow curves](image)

3. Results and discussion
3.1. Springback and warping of U-profiles
In Figure 6 the ratio of unloaded inner bending radius $r_{IR}$ to loaded inner bending radius $r_I$ is displayed as a measure of springback dependent on the partial heating temperature for 2.5 mm and 1.5 mm thick
specimens. Springback stays constant till 200 °C heating temperature for 1.5 mm thickness and till 400 °C for 2.5 mm thick profiles. At higher temperatures, springback decreases approximately linearly with the lowest obtained springback at 600 °C, with a higher decrease for profiles of lower thickness. The maximum springback reduction amounts to 69 % for 1.5 mm thick profiles and 48 % for 2.5 mm thick profiles.

The reduction of springback occurs due to the thermal softening of the material (Figure 5 (b)). As the flow stress in the heated area is reduced, the necessary bending moment to produce the desired bending radius is decreased. Lower bending moments generally lead to a reduced springback.

The springback reduction only occurs if a threshold temperature is reached. The reason for this is the positioning of the heated zone. The maximum bending moment occurs at the x-position of the counter-roll. When the profile is at room temperature, bending would start at this position. By partially heating the profile the position of the bending zone is shifted to the heated area. If the profile strength is decreased enough by thermal softening the profile will bend in the heated zone, while for lower temperatures the profile will still bend at the position of the counter-roll. As the bending zone is still at the position of the counter-roll, at which the profile is at room temperature, for lower partial heating temperatures the bending moment will not decrease. This concludes that springback is only reduced if the forming zone for the process is located in the heated region. For profiles with lower thickness the stiffness is lower. This means less heating suffices to change the position of the heated zone for profiles of lower thickness.

The profile warping is evaluated dependent on the profile arc length starting at the position of the counter roll (Figure 7). Warping develops approximately linearly over the arc length. For both profile variants warping decreases with increasing partial heating temperature. For the lower thickness (Figure 7 (a), maximum warping at room temperature is 60 % less for the 2.5 mm profiles than for the thinner counterparts. Compared to room temperature, the maximum warping reduction is 68 % for 300 °C and 83 % for 600 °C partial heating temperature for the 1.5 mm thick profiles. The warping reduction in the 2.5 mm thick case (Figure 7 (b) is 40 % for 300 °C and 69 % for 600 °C partial heating temperature.

![Figure 6. Profile springback ratio for 1.5 mm and 2.5 mm thickness](image)

![Figure 7. Related profile warping angle for 1.5 mm (a) and 2.5 mm (b) thickness](image)
As the stiffness of the profile with higher thickness is larger the initial warping is lower than for profiles of lower thickness. In fact, the torsion stiffness for 2.5 mm thick profiles is 78% higher than for 1.5 mm thick profiles (room temperature). As the flow stress decreases in parts of the profiles, the stiffness of the whole profiles is decreased as well. The partial heating temperatures are the same for both profile types and geometrically only thickness changes. This concludes that the warping for higher partial heating temperatures and higher profile thicknesses is lower.

Warping, just as springback, depends on the bending moment of the profile. Still, the decrease in warping is higher than the decrease in profile springback for the same geometry and partial heating strategy. This means, that the warping reduction is not fully achieved through a global stiffness reduction of the profile, but a combined effect of the stiffness reduction and the shift of the shear center position (see section 2.1) which has been proven for L-profiles [7] but needs to be analysed more thoroughly for the U-profiles.

3.2. Comparison of warping and springback between U- and L-profiles

To confirm the transferability of the results in this work with other profiles the results for springback and warping are compared to the behaviour of L-profiles with the same heating strategy and otherwise same geometry [7] (Figure 8). Both L- and U-profiles consist of S500MC material with 2.5 mm thickness and a width of 40 mm.

As for the 2.5 mm and 1.5 mm U-profiles, the springback for the L-profiles is constant until a threshold temperature is reached (Figure 8 (a). This threshold temperature for the L-profiles is 300 °C and is in between the values for the U-profiles (200 °C for 1.5 mm thick U-profiles and 400 °C for the 2.5 mm thick variant). After this temperature the springback also decreases linearly for L-profiles. The springback for the L-profiles a room temperature is 24% lower than for the U-profiles. At 600 °C partial heating temperature this difference is 33%.

Profile warping for L-profiles behaves different than for U-profiles (Figure 8 (b). While initially the warping for L-profiles is increasing linearly like the U-profile data, the warping then remains constant after a threshold is reached. This threshold depends on the partial heating temperature. For L-profiles warping at a maximum arc length for the room temperature case is 50% lower than for U-profiles. At 600 °C the difference amounts to 39%. The maximum warping reduction for the L-profiles is 76% while it is 69% for the U-profiles.

![Figure 8](image-url). Comparison between results for L-profiles and U-profiles, (a) springback ratio, (b) related warping angle

Compared to U-profiles, the bending stiffness is 62% lower and torsion stiffness 40% lower for L-profiles at room temperature. Additionally, a larger fraction of the total cross-section is heated for the L-profiles (50% for L-profiles and 33% for U-profiles) the stiffness reduction is higher. As the bending stiffness for the L-profiles is lower, less springback occurs. The warping reduction is nearly the same as
for the U-profiles. This could mean that for this heating strategy and this combination of profile cross-sections the change of the shear center position is the same, which will be investigated further in the future.

4. Conclusion

It has been proven that partial heating can successfully reduce warping and springback in bending of profiles with an asymmetric cross-section in regards to the force initiation axis. A warping reduction of 83 % and a springback reduction of 69 % have been achieved in the case of bending U-profiles. The springback reduction can be attributed to the global profile stiffness due to the thermal softening of parts of the profile resulting from partial heating. As the bending moment is reduced for partial heated profiles, so is the springback. Consequently, cross-sections of lower stiffness (e.g. L-profiles), lower thicknesses, and thermal softened profiles have lower springback.

Profile warping for U-profiles can be reduced by the use of a partial heating strategy. The reduction of warping can be attributed to the shift of shear center position through the partial heating strategy. The change of shear center position reduces the lever arm for torsion.

The new investigations show that warping reduction for bending of U-profiles through partial, cross-sectional heating is possible. Combining this knowledge with the warping behavior of L-profiles with partial heating [7], it can be expected that warping and springback reduction for other profile types is possible using this heating strategy. As the heating is necessary for the geometric accuracy of the profiles, future work will explore the possibility to use the heat for tailoring of the mechanical profile properties.

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