

VARIABLE CROSS-SECTION DRAW BENDING OF SHEET METAL WITH FLEXIBLE TOOLS¹Diego Ignacio MIRANDA SILVA, ¹Norman MOHNFELD, ¹Johanna UHE, ¹Bernd-Arno BEHRENS¹ *Leibniz University Hannover, Institute of Forming Technology and Machines, An der Universität 2, 30823 Garbsen, Germany, EU, mirandasilva@ifum.uni-hannover.de, mohnfeld@ifum.uni-hannover.de, uhe@ifum.uni-hannover.de, behrens@ifum.uni-hannover.de*<https://doi.org/10.37904/metal.2026.5241>**Abstract**

In lightweight construction, particularly in the automotive sector, load-adapted profiles are required to reduce weight whilst maintaining the necessary stiffness. Since chassis and body components account for approximately 41% of total vehicle weight, reducing their weight by optimising load-bearing capabilities is essential. This weight reduction can be achieved using thinner profiles made from high and ultra-high strength materials such as 1.5528 (22MnB5), which can achieve tensile strengths of 1,500 MPa via martensitic transformation. Additionally, the production of load optimised components creates the need for secondary form elements in sheet metal components, such as beads and variable cross sections for load-optimised components. Components with varying profile geometries and secondary form elements can be produced by roll forming or draw bending using flexible tools, but the flexibilization produces secondary effects during forming, which make the forming process challenging. This study focuses on flexible draw bending of 1.5528 sheet metal profiles with variable cross sections under continuous in-situ tempering. The variable cross sections allow for a load-optimised design, whilst a central bead is introduced as secondary form element to increase the overall stiffness of the component. Tool kinematics are analysed in order to identify geometric discrepancies and their causes using the finite element software Simufact.Forming.

Keywords: Sheet metal forming, draw bending, variable cross-sections, finite element method**1. INTRODUCTION**

By using a flexible and adaptable part design and manufacturing process, a wide range of products and product families can be produced via draw bending [1]. In sheet metal forming, particularly in the automotive sector, a large variety of profiles are required for vehicle frames. The industry's pursuit of sustainability demands parts to be lighter while maintaining their mechanical strength [2, 3]. Mainly two processes can be used to produce variable cross-section profiles in sheet metal forming: roll forming [4] and draw bending [1]. Draw bending utilizes simpler and less expensive tooling as roll forming. It represents a linear die movement process in which a flat metal sheet is drawn through a die in single-stage or multi-stage operations, with the blank clamped behind the tool [5].

Whilst conventional draw bending processes are well established, they lack the adaptability to produce profiles with variable cross-sections [1]. Such cross-sections can be achieved through flexible tooling with an additional degree of freedom in the forming machines [6]. However, introducing flexibility into draw bending processes leads to unintended mechanical or geometrical changes that occur during and after forming due to complex, non-linear deformation and localised path-dependent loading. These are often referred to as secondary effects [4, 7, 8]. These effects arise primarily in the form of web-warping, longitudinal bowing and flange wrinkling. These are caused by transversal non-uniformity of longitudinal strain, and excessive compressive longitudinal stresses in cross-sectional transition zones, where the width or height of the cross-section varies [4].

Further improvement of mechanical properties in formed profiles can be achieved through post-forming heat treatment or tempering. Conventionally, heat treatment is performed as a separate step in external furnaces. Forming of heated material offers additional advantages: increased formability, reduced friction, and earlier plastification of the blank. Integrating inductive heating into the forming machine reduces heating and transfer costs, eliminates the need for die heating, and achieves both improved formability during forming and enhanced mechanical properties in the final component [2]. Furthermore, it enables tailored tempering integrated into the forming process, further shortening the process chain and increasing efficiency. This integration also enables the aforementioned martensitic transformation of the blank through air jet cooling after forming, greatly increasing its tensile strength [9]. A prior study performed by Oehlmann et al. analysed secondary form elements, specifically central beads, and their influence on the final stiffness of profiles whilst also subjecting the part to local tempering [9]. Experimental investigation and optimization of flexible processes is cost-inefficient due to numerous coupled process and material variables. Finite element (FE) simulations reduce the impractical costs associated with experimental trial and error [9]. The present investigation builds on the work of Oehlmann et al. by extending it to U-profiles with variable cross-sections whilst maintaining consistent flange dimensions.

2. METHODOLOGY AND MATERIALS

The numerical investigation is carried out using the FE software Simufact.Forming v25.2. For modelling a thermo-mechanically coupled analysis was used. The process consists of a sheet metal blank that is clamped behind the forming die and pulled through it. The basic setup of the simulation model is depicted in **Figure 1 a)**. Ahead of the dies, localized inhomogeneous heating raises the temperature to 900 °C. After forming, the blank is rapidly cooled from 900 °C to 20 °C by air jet cooling upon leaving the drawing die. Heating and cooling were modelled using near field contact conditions for simplification

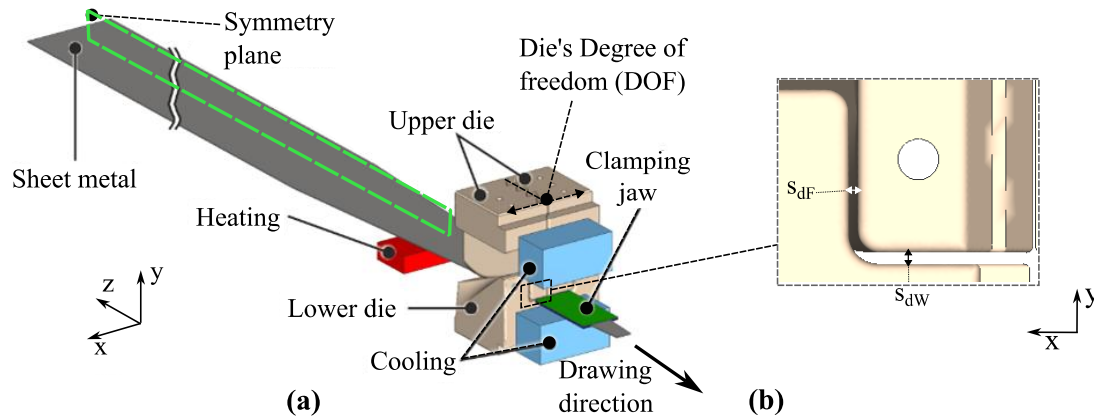


Figure1: a) Simulation model setup and b) detail of die's drawing gaps

The forming die itself consists of two die halves that have translational degrees of freedom (DOF) along the x and y direction. This allows the die halves to be adjusted whilst forming, enabling the forming of varying cross-sections whilst maintaining constant flange height along the profile length. **Figure 1 b)** shows the drawing gap of the upper and lower dies for the flange s_{dF} and for the web s_{dW} . Independent movement of the die halves enables selective enhancement or reduction of the drawing gap. Extensive experimental and numerical analysis of process and material parameters has been conducted in previous works [9]. These include phase-specific flow curves as well as time-temperature-transformation and continuous-cooling-transformation diagrams, which enable calculation of remaining microstructural phases after forming and their respective percentages and distribution [9]. The heating and cooling have been modelled with a heat transfer condition between the inductor and cooling with the sheet metal blank. The initial phase composition has been determined to $w_{Ferr,ini} = 41.4\%$ and $w_{Perl,ini} = 51.6\%$ for ferrite and perlite respectively. An adaptive,

temperature-dependent coefficient of friction (COF) has been used [10]. The complete numerical parameters for this study are listed in Table 1.

Table 1 Summary of model's boundary conditions

Parameter	Description	Values
Symmetry	DOF along symmetry plane	YZ-plane
Material	1.5528 with phase transformation data	$T_{Ac3} = 808.36^{\circ}\text{C}$
Process temperatures	Initial blank temperature	$T = 20^{\circ}\text{C}$
	Target heating temperature	$T = 900^{\circ}\text{C}$
	Die temperature	$T = 20^{\circ}\text{C}$
	Ambient temperature	$T = 20^{\circ}\text{C}$
Heat transfer	Cooling of sheet metal	$\alpha_{cooling} = 2 \cdot 10^5 \text{ W}/(\text{m}^2 \cdot \text{K})$
	Inductive heating	$\alpha_{inductor} = 3,950 \text{ W}/(\text{m}^2 \cdot \text{K})$
Coefficient of friction	Die to sheet metal contact	Temperature-dependent
Clamping jaws	Modelling of clamping jaws	Sticking contact to jaw surface
Tool kinematics	Tool movement during forming	Tabular displacement
Mesh parameters	Average mesh size	$d_{mesh} = 2.5 \text{ mm}$
	Number of elements across thickness	$n_{thickness} = 3$
Initial microstructure phase composition	Ferrite	$w_{Ferr,ini} = 41.4\%$
	Perlite	$w_{Perl,ini} = 58.6\%$

Finally, the process modelling has been validated in [9] through experimental analysis. The draw bending process produces a U-profile with varying cross-sections. **Figure 2** shows the tailored blank with its dimensions before forming.

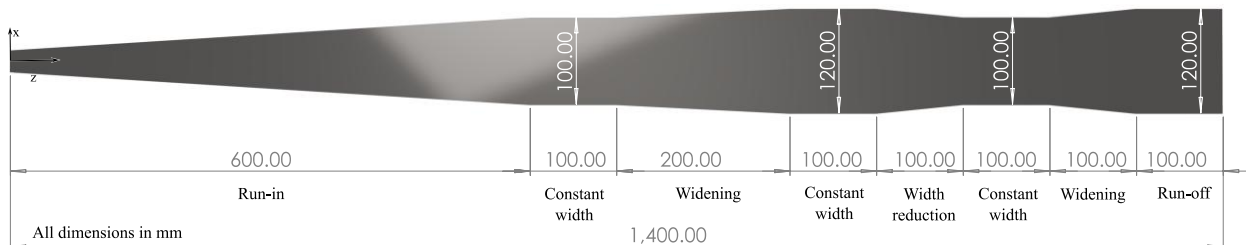


Figure 2 Dimensions of the tailored blank prior to forming

As depicted in **Figure 2**, the blank has a lead-in section followed by the main forming zone and a run-off section at the blank's end. The total blank length is 1,400 mm with a thickness of 1.5 mm. The drawing speed is set to 10 mm/s, whilst the translation speed of the dies is calculated according to the section width being formed.

3. RESULTS AND DISCUSSION

An initial simulation with standard parameters serves as a baseline for improvement and comparison. The baseline simulation consists of a constant draw gap of $s_{dF} = 1.85 \text{ mm}$, a desired constant flange height of $h_F = 20 \text{ mm}$ after the lead-in section and heating to 950°C . The blank's final shape after forming is shown in **Figure 3 a)** with the logarithmic strain and evaluation paths. One along the web centre (green), the second on topmost side of the flange (orange). **Figure 3 b)** shows the web and flange geometries. To ensure the observed forming defects do not arise primarily from local heat treatment effects, a simulation with no inductive heating at room temperature is conducted for comparison. The formed profile displays the same shape defects as the heated specimen. The profile web remains at zero height for most of its length; however, a substantial increase is observed in the section where the profile width undergoes cross-sectional variation. This is a well-known forming defect in flexible forming, observed in both flexible draw bending [7] and roll forming. This effect

is nearly completely counteracted when the profile width is reduced to its original value. Apart from this, no further effects are observed along the profile web.

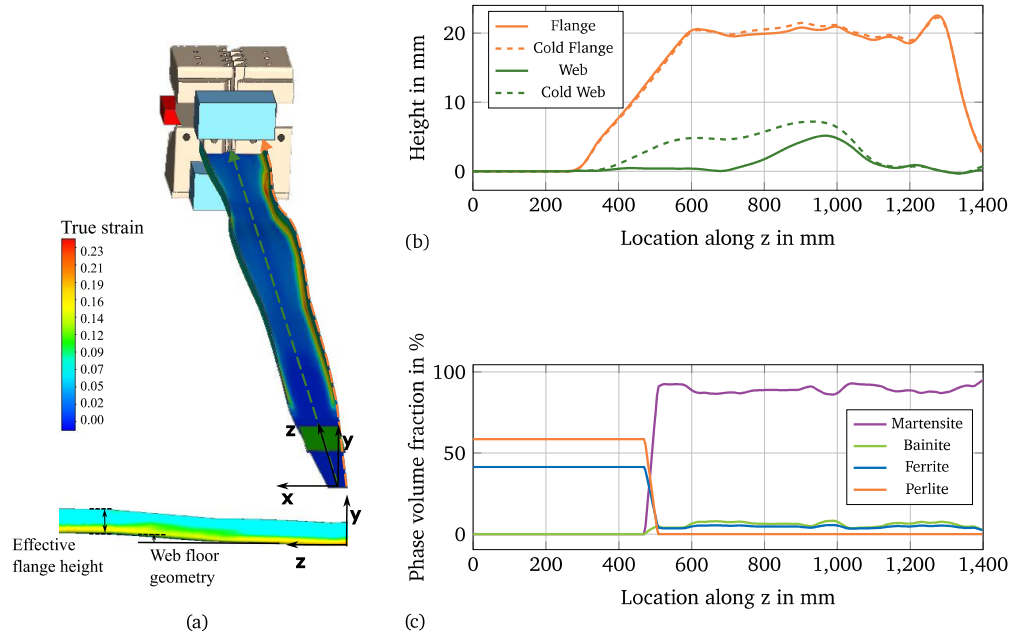


Figure 3 a) U-Profile after forming, b) comparison of profile's web and effective flange height, and c) microstructural phase distribution over profile length

The flange displays no wrinkling and remains at constant height along the profile length, excluding the lead-in and run-off areas. Analogous to the web, the flange rises in the section of width variation; this is expected, since the entire profile is subject to longitudinal bowing. Subtracting the profile rise from the flange height shows that it remains fairly constant around the desired value of 20 mm. A comparison to the ideal flange height shows an error of $RMSE_{base} = +0.6575$ mm across the flange length. The effects of local tempering are shown in **Figure 3** c) and the respective residual microstructural phase distribution after forming. The inductor is located at $z = 460$ mm from the blank's forward edge at the start of the process, hence not affecting microstructure phases in the first part of the blank. The initial phase composition of ferrite and pearlite decreases rapidly as the blank is austenitised due to heating to 900 °C before reaching the forming dies. After forming and rapid cooling, the pearlite fraction is completely eliminated. Small fractions of bainite and ferrite are present, whilst the larger fraction, with a mean of 89.3%, is martensite, indicating successful heat treatment. Along the web, the profile retains its thickness but displays longitudinal bowing, especially in zones where the cross-section varies, as seen in **Figure 3** b). This is observed predominantly between $z = 600$ mm and $z = 1,100$ mm and is caused by unbalanced longitudinal strains across the profile width. During widening ($700 \text{ mm} < z < 900 \text{ mm}$), the profile and flange rise. Conversely, during cross-sectional width reduction ($1,000 \text{ mm} < z < 1,100 \text{ mm}$), the flange and web sink. In warm-formed profiles the bowing is observed between $z = 600$ mm and $z = 1,100$ mm, in the cold formed one around $z = 400$ and $z = 1,100$ mm. Longitudinal bowing is greater in the specimen formed at ambient temperature than in the inhomogeneous heated one. Thus, it can be concluded that the shape discrepancies arise mainly from mechanically induced unbalanced stresses and strains during forming, which are exacerbated when forming at ambient temperature. This can be attributed to improved material flow and relaxation at elevated temperatures, where temperature gradients are less pronounced than those in cold forming, as well as reduced spring back effects. Comparison of the flange height to the ideal flange shows an error of $RMSE_{cold} = +0.6961$ mm

The possibility of varying the drawing gap during forming to influence target areas is studied as well as a means of counteracting bowing in the width variation zone. In widening zones, the gap can be decreased to enhance tension in the flange and reduce compressive strains after forming. Conversely, in narrowing zones, the gap can be widened to allow the material in the flange to relax and mitigate residual tensile stresses and strains. This is achieved through independent translation of the drawing dies during cross-sectional width changes. In the initial simulation, the drawing gap at the flange is kept constant at $s_{dF} = 1.85$ mm. It is increased and decreased to $s_{dF,inc} = 1.95$ mm and $s_{dF,dec} = 1.7$ mm, respectively. Additionally, the web drawing gap is adjusted, decreasing from the nominal $s_{dW,N} = 2.35$ mm to $s_{dW,dec} = 1.75$ mm in width variation zones and returning to its nominal value in constant-width zones. The results are shown in **Figure 4**, focusing on the width variation area. **Figure 4 a)** shows the profile web and flange geometry. An improvement in the final flange height geometry can be observed, whilst profile bowing remains virtually unchanged. As can be seen in **Figure 4 b)**, the flange height of the adaptively formed part better adheres to the desired flange height of $h_F = 20$ mm, displaying an error of $RMSE_{adaptive} = +0.5780$ mm as compared to the $RMSE_{base} = +0.6575$ of the baseline parts, a reduction of 12.1%.

This positive effect can be achieved by mitigating the unbalanced strains arising from flange bending. By restricting the web from elastically deflecting whilst the flange is formed and distributing strains over a greater surface area, the peak strain difference across the cross-sectional width is reduced, thereby decreasing bowing. As shown in **Figure 4 b)**, whilst the web and flange rise in the aforementioned section, the local flange height remains at approximately the desired value of 20 mm. The flange shows no signs of wrinkling or other geometrical defects.

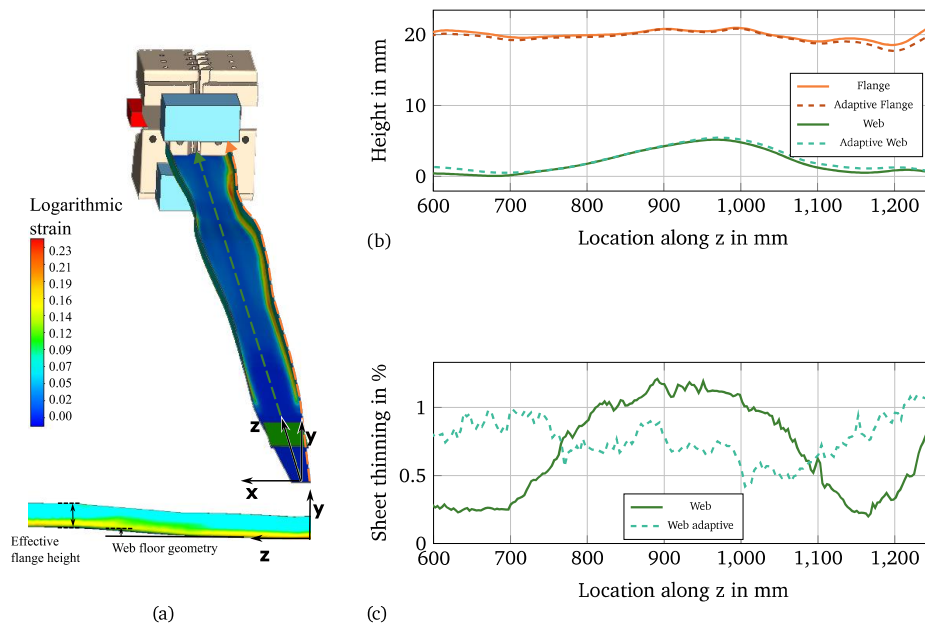


Figure 4 Effects of adaptive drawing gap on final geometry and sheet thinning, a) U-profile, b) profile's web and effective flange height, and c) sheet thinning along the profile's web

Figure 4 c) shows sheet thinning for both nominal and variable drawing gap variants. The non-adapted sheet displays a rise and fall, with a maximum value of 1.21% at the centre. The profile with varying drawing gap shows a less pronounced trend compared to the nominal simulation, with a local maximum of 0.97% at the same location. Varying the drawing gap improves blank thinning along the web from $z = 780$ mm to $z = 1,080$ mm. This measure achieves approximately 20% reduction in thinning in the $z = 780$ mm to $z = 900$ mm

zone, after which the difference from the nominal profile increases, showing further improvement up to $z = 1,080$ mm. Here, thinning is reduced by up to 36%. Whilst thinning is slightly increased at transition zones, the improvement in the width variation zone is significant.

4. CONCLUSION AND OUTLOOK

This study demonstrates that exploiting forming die kinematics can improve component quality, particularly in flexible forming where this flexibility introduces non-linear, non-uniform longitudinal strains. The comparison with a cold-formed part reveals that shape discrepancies arise primarily from mechanically induced non-uniform strains rather than from thermal effects of tempering. An adaptive drawing gap reduces blank thinning in the web area and minimizes web and flange bowing whilst also improving overall flange geometry.

With simple adaptive die paths geometric discrepancies in flexibly formed profiles could be reduced. Controlled-path dies coupled with sensors could provide further improvement by minimizing discrepancies arising from complex mechanical states in flexible forming. Furthermore, flexible blank holders offer an additional means of stabilizing the blank during forming, reducing web and flange bowing and thereby minimizing geometric discrepancies in the final product.

ACKNOWLEDGMENTS

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 507245889.

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