Segmented blank holder concept to influence the forming zone during incremental bending

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Abstract. Decreasing batch sizes and a simultaneous increase in the number of variants are developments in production technology that can no longer be managed economically using conventional mould technology with rigid, product-specific functional surfaces for semi-finished products. Individual or even in-line reconfigurations of the tool's functional surfaces are being investigated to meet production requirements. Moreover, the goal is to control these surfaces during the process to compensate fluctuations, e.g. in semi-finished products. Incremental swivel bending (ISB) is a process for flexible bending forming in which the bending moment is transferred to the semi-finished product by friction by means of the clamping surfaces of the blank holder. In addition to the geometric and mechanical properties of the semi-finished product, the contact normal force and friction are responsible for the size and shape of the forming zone. In this paper, established analytics are utilized to present a tool concept that enables the clamping force distribution to be specifically adjusted by means of adjustable segmented hold-down surfaces with a vertical degree of freedom and, as a result, the size and shape of the forming zone to be influenced. The potential for extending the limits of forming technology is then discussed regarding the numerically determined local strain distribution through the dynamic loading and unloading of the clamping surface segments during incremental forming with the overall goal to achieve an in-process controllable material flow during sheet metal forming.

Introduction

Incremental forming processes offer a high degree of flexibility regarding the component geometry to be achieved, as the sequence of increments can be individually selected. At the same time, these processes fulfil current requirements, such as increasing variant diversity with simultaneously decreasing batch sizes, as one or more additional degrees of freedom allow components to be produced independently of the tool geometry [1-3].

Compared to continuous forming processes, incremental forming also has the advantage that higher degrees of deformation can be achieved due to the highly localised strain distribution [4-6]. Due to the freedom to sequence the forming increments, incremental processes offer an additional degree of flexibility compared to continuous processes. However, this requires a deep understanding of the forming zone and strategies to control the overlapping deformation zones [7].

For individualised and variant-intensive production, kinematic processes such as incremental swivel bending (ISB) have become established, which, for example, enables targeted adjustment of the strain curves by shifting the bending axis [8].

The sequential process repeats a sequence of production steps to line up individual bend increments to form a bend. Alternating bending directions or positioning the profile in opposite directions enables alternating bending and offers the potential to integrate geometric functions to produce side members for cars, for example (see Fig. 1.).

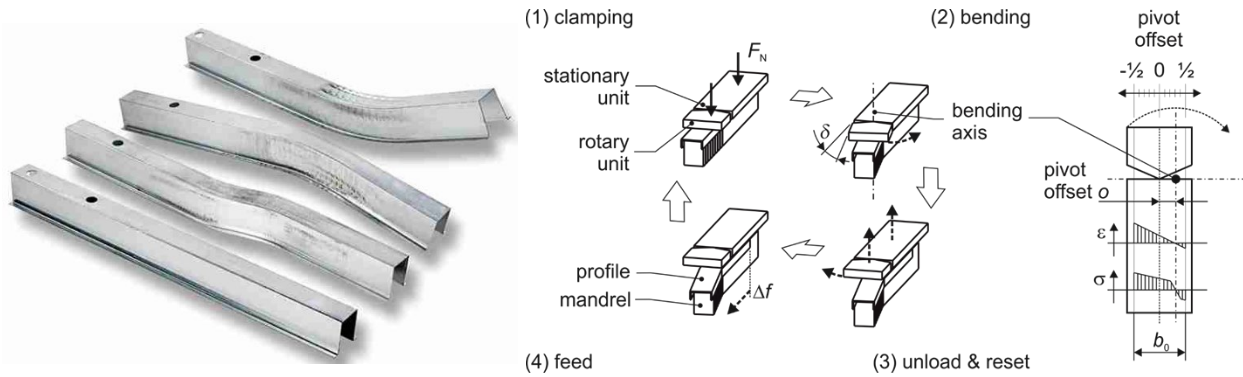

Fig. 1. left: hat profiles formed using the ISB process for the automotive industry (side members), right: process sequence of incremental swivel bending.

In the ISB process, the bending moment is transmitted by the clamping surfaces, which apply frictional tensile or compressive forces in the longitudinal direction of the semi-finished product. In addition to the geometric and mechanical properties of the semi-finished product, the contact normal force and the state of friction - which occurs between the clamping surface and the semi-finished product - are responsible for the size and shape of the forming zone [9].

The forming zone (see red shaded area Fig. 2a) develops after the yield point of the material is exceeded within the bending gap of the clamping tools rotating against each other and below the clamped contact surfaces. In the tensile stress range of the bending stress distribution, the material is plastically thinned within the forming zone angle γ due to the transverse strain (see Fig. 2b). The contact area A_c between the blank holder and the semi-finished product is reduced so that the contact normal stress increases at a constant press closing force and the frictional shear stress increases in direct proportion [10].

The prerequisite for a stable bending process is ensured by maintaining static friction, as slipping of the material under the clamping surfaces leads to an uncontrolled process sequence and - in the case of profile bending - to severe component twisting. Consequently, the extraction of the material must be ensured by maintaining the static friction in the form of a minimum requirement for the clamping force. In the further process sequence, the applied bending moment is only transferred to the remaining contact surface of the tool and solidifying materials also require a sharply increasing forming force. As a result, the minimum force requirement is expected to increase during the bending process [11].

There is therefore a requirement to design the functional surface for transmitting the clamping force and ensuring frictional locking in such a way that contact between the clamping surface and the semi-finished product is maintained and a contact pressure distribution that can be adjusted during the process can be realised.

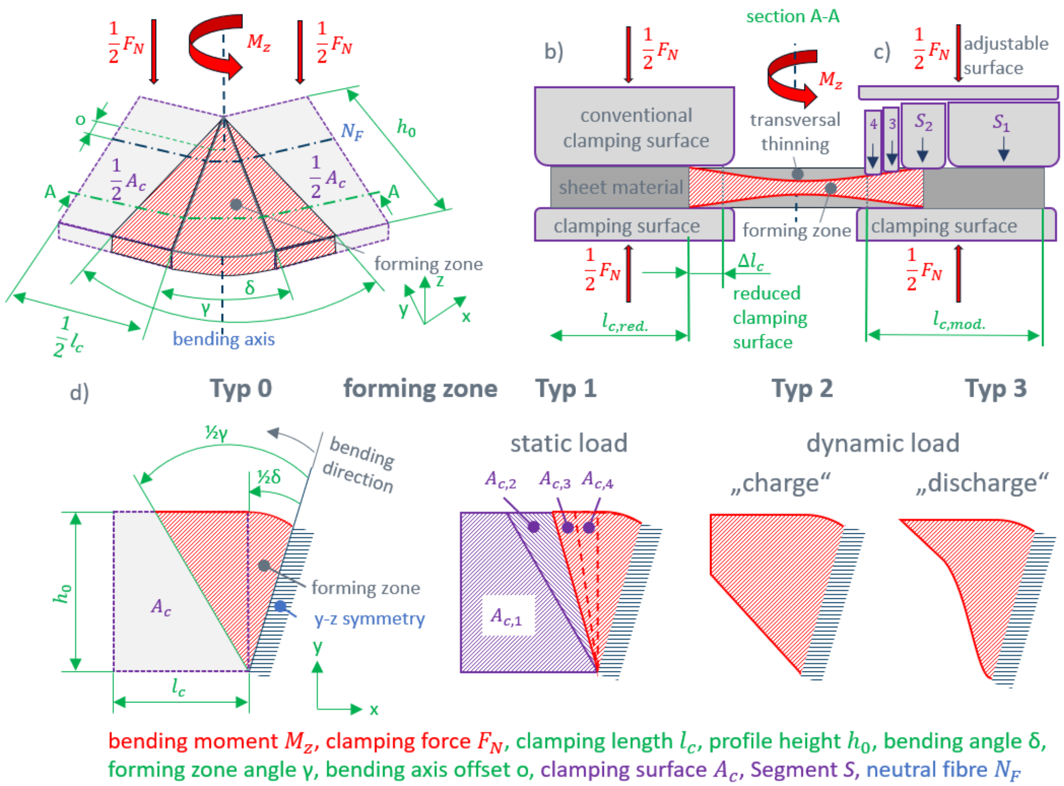

Fig. 2. a) Bending in the plane and formation of the forming zone, b) Sectional view with transverse thinning and reduced clamping surface, c) Adjustable surface follows the thinning, d) Predicted characteristics of different forming zones due to static or dynamic load.

Theoretical Background and Calculations

The ISB process has been demonstrated to work substantially under the principle of frictional engagement. In detail, the bending moment to form a single increment is transmitted by means of a firm fixation of the part in the heavily loaded clamping tools. Traction is a necessary premise for this forming principle since material must be prevented from slipping through the clamping tools to achieve a determined forming process. The central analytical description of the process relates the evolving forming zone to the applied process parameters as well as the mechanical material properties and geometrical relations. By the description of the forming zone, the corresponding strain gradient and the achieved curvature are determined for the bending operation to layout the process for a given application in production technology.

According to FROHN-SÖRENSEN [11], the forming zone angle γ is given by the relation

$$\gamma_{1/2} = -\frac{q_1}{2} \pm \sqrt{\left(\frac{q_1}{2}\right)^2 - q_2} \tag{1}$$

with the substitutions

$$q_1 = -\left(\frac{2}{3}\frac{E \cdot \delta}{R_e} + 2\delta + \pi\frac{l_{c,0}}{h_0} + \frac{\mu_0 \cdot F_N \cdot E \cdot \pi}{\sqrt{3} \cdot 2R_e \cdot m \cdot {h_0}^2}\right) \tag{2}$$

and

$$q_2 = \delta\left(\left(\frac{2}{3}\frac{E}{R_e}+1\right)\cdot\left(\delta+\frac{\pi\cdot l_{c,0}}{h_0}\right)+\frac{\mu_0\cdot F_N\cdot E\cdot\pi}{\sqrt{3}\cdot 2R_e\cdot m\cdot {h_0}^2}\right) \tag{3}$$

where E is YOUNGS´s Modulus of Elasticity and R_e is the yield strength of the material. With respect to the process, F_N is the clamping force applied on both clamping tools and μ_0 is the static friction coefficient where tool surfaces and material are in contact. $l_{c,0}$ denotes the clamping length and h_0 the profile width. For the analytical process model, a bilinear hardening curve according to GERLACH [12] is applied for mathematical reasons where m is the inclination of the linear interpolation of hardening between yield strength and ultimate tensile strength R_m. Besides the linear expression in the elastic region according to HOOKE's law [13], the bilinear hardening curve is described in the plastic deformation region by

$$k_f = m\cdot\varepsilon + R_e\cdot\left(1-\frac{m}{E}\right) \tag{4}$$

where m is expressed according to

$$m = \frac{R_m(1+A_G)-R_e}{A_G-\varepsilon_{el}}. \tag{5}$$

When comparing Eq. 1 with practical bending experiments and simulations, it has been observed that the forming zone angle strongly increases over the first few degrees of bending angle δ, which is imposed by the clamping tools. Given by the geometrical relation of the clamping length $l_{c,0}$ and the profile width h_0, γ converges until an ultimate forming zone angle γ_{ult} and would stay on this value with any further increase of bending angle. γ_{ult} is calculated according to

$$\gamma_{ult} = 2*tan^{-1}\left(\frac{l_c}{h_0}\right). \tag{6}$$

Once the forming zone is determined, longitudinal strain ε_x in the centre of the forming zone is expressed by

$$\varepsilon_x = \frac{\Delta l}{l_0} = \frac{\delta}{\gamma-\delta}\,. \tag{7}$$

With the determination of strain, the unloaded bending angle δ_u is calculated from the bending angle given by the process δ minus the springback angle δ_{SB} which results from the elastic release of residual stresses. According to WITTEK *et al.* [14], the unloaded incremental bending angle δ_u is assumed as

$$\delta_u = \delta-\delta_{SB} \approx \delta\left(1-3\cdot\frac{R_e}{E}\cdot\frac{1}{2\varepsilon_x}\right). \tag{8}$$

For incremental bending, multiple of these aforementioned forming zones γ are superposed. A number of n bending increments of angle δ are combined with incremental feed spacings with the distance Δf in an alternating process sequence. With the unloaded bending angles being calculated according to Eq. 8, a representative bending radius R can be assumed from the discontinuous manufacturing method ISB. By the relation of the curvature κ being the inverse expression of the radius, the arc manufactured by incremental bending processes is obtained by the following relation according to [15]

$$\kappa_{NF} = \frac{4}{\Delta f\cdot\left(\frac{1}{\sin\frac{\delta_u}{2}}+\frac{1}{\tan\frac{\delta_u}{2}}\right)}\,. \tag{9}$$

For the calculation of curvature at the strain-neutral fiber κ_{NF}, it is important mentioning that the unloaded bending angle must be justified by strain hardening in Eq. 8 since multiple forming zones overlap in the incremental sequence.

The number of superposed forming zones is denoted by the integer *SP*. With the successively increasing integer variable *i* for the incremental process sequence, strain obtained from incremental bending $\varphi_{x,s}$ is expressed by a sum formulation according to

$$\varphi_{x,s} = \sum_{i=1}^{SP} \ln\left(\frac{\delta \cdot \left(1 - 3 \cdot \frac{k_{f,i-1}(\varphi_{x,i-1})}{E} \cdot \frac{1}{2 \cdot \varepsilon_x}\right)}{\gamma - \delta \cdot \left(1 - 3 \cdot \frac{k_{f,i-1}(\varphi_{x,i-1})}{E} \cdot \frac{1}{2 \cdot \varepsilon_x}\right)} + 1\right) \tag{10}$$

where hardening $k_{f,i-1}$ is a function of strain $\varphi_{x,i-1}$. With the equations above, the forming potential of the herein presented novel tooling concept is predicted.

Tool Concept Development

A tool concept was developed with the overarching aim of influencing the forming zone in terms of its geometry and gradient. This considers the existing analysis to the effect that the maximum forming zone angle γ_ult converges asymptotically towards a limit value of 90° depending on the bending angle δ and assuming square hold-down surfaces. To ensure that the strain distribution is as localised as possible and thus higher degrees of deformation can be achieved [4,5], the approach of reducing the forming zone angle was pursued. The tool concept is based on the investigations from [16,17] and divides the blank holder surface in the upper part of the tool. This creates individual surface segments that allow the clamping force distribution and consequently the generated contact normal stress - which acts on the sheet metal strip - to be varied.

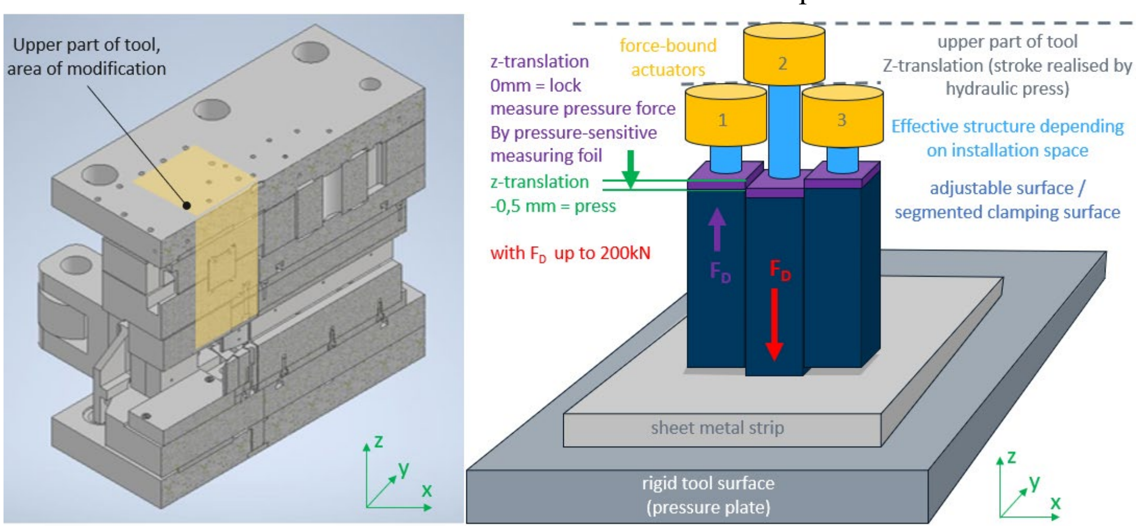

Fig. 3. left: ISB-experimental tool (CAD sectional view) with modification area in the upper part marked in orange, right: tool concept for static adjustment and dynamic control of the segmented blank holder (schematic).

The concept includes the following approaches (see Fig. 3):

- Geometry: The triangular geometry of the segments is based on the forming zone that forms in the event of bending under tensile stress. The geometries of the individual segments become finer the more angle pieces divide the area of the forming zone.
- Position: The symmetry plane (see Fig. 2. y-x symmetry) is referred to as the flow sheath. This is where the maximum strains are present in the current process design. The plane of symmetry and the centre of rotation of the bending axis lying on it are defined in the concept

(and for the case of bending under pure tensile stress) as the origin of the angle pieces. All segments meet here.

- Kinematics: The segments are supported by one vertical degree of freedom so that they can perform a translational movement orthogonal to the sheet plane. Due to the machine and tool compliance, the current design requires a translation of 0.5 mm to be able to follow the transverse thinning of the material in the thickness direction and thus maintain the condition of static friction between the clamping and surface of the semi-finished product.
- Measuring technology: To measure the process-related compressive forces, a surface pressure-sensitive film is mounted on the head side of each segment. To prevent the film from being destroyed by any shear stress, it is mounted between hardened plate inserts. Due to the fine subdivision of the hold-down surface in conjunction with the high pressures, this results in an installation space problem that severely limits the use of load cells.
- Actuators: Due to the different levels of complexity, two basic distinctions are made. On the one hand, the concept already enables static, manual adjustment of the compressive force without actuators, for example by using a thin sheet to individually support each segment, and on the other hand, dynamic control of the clamping force. The latter includes various methods for influencing the geometry and spread of the forming zone. This allows the hold-down segments to be loaded and unloaded over time and locally based on the subdivision. Due to the high energy density required, which results from the requirement for fine subdivision of the blank holder surface in combination with the clamping force of up to 200 kN to be realised, short-stroke hydraulic cylinders in the high-pressure range of 700 bar are used as actuators. The hydraulics enable force-based control and proportional measurement of the applied pressure force per segment via proportional valves. The pressure force is measured using pressure transmitters. The cylinders can be controlled individually and can move independently of each other with a stroke tolerance of 0.5 mm in a range of 0-5 mm. The cylinder force is then transferred to the segments.
- Active structure: Based on the preliminary work [18], a high-performance, i.e. the most compact, rigid, load bearing and load transferring active structure possible is developed, which realises the required kinematics with the desired accuracy. Furthermore, the active structure allows the actuators to be nested and thus enables the required compact design with sufficient accessibility.

Finite-Elemente-Simulation

A quasi-static, elasto-plastic deformation analysis of in-plane bending was implemented and calculated in the software ABAQUS CAE 2021. Based on the finite element method (FEM), the novel, segmented tool concept was implemented to study the effects of the process kinematics on the resulting forming zone. To this aim, a sufficient representation of the contact pressure distribution must be simulated since the process bases on the principle of frictional engagement. It was proven in preceding studies [11,16] and literature [19] that solid elements with elastic material properties are necessary to represent tool elasticity and thus obtain a valid contact pressure distribution and, in consequence, forming result.

Here, the sheet metal blank was discretized by a mesh of solid finite elements of 8-node linear brick type (C3D8) with a size of 1x1 mm in plane and 7 elements over thickness (see Fig. 4). A dual phase steel material with significant hardening behaviour – a HCT780X sheet metal steel of 1.5 mm thickness – was modelled in the simulation by means of a density of 7.85 kg/dm³, a YOUNG´s modulus of 215 GPa and a Poisson Ratio of 0.3. Isotropic plastic deformation behaviour was assumed, and hardening was modelled by applying SWIFT/KRUPKOWSKY´s law. The segmented tool surfaces in contact are represented by the same type of hexagonal finite elements with a uniform mesh size of 2 mm and by using the same elastic parameters.

In the process model, the segments were loaded in a way proportionally to their contact surface so that the accumulated force from all segments would achieve the nominal press load which should be applied to the process for firm clamping conditions. In detail, a 45° and two 22.5° segments were represented in simulation where the first is loaded with half of the nominal clamping force and the latter segments are loaded with a quarter of the nominal load. Since a symmetric tool setup is suggested for the incremental bending process ISB, a central symmetry constraint is applied and only one of the bending tools is modelled. Under load, the clamping tool would then pivot around the bending axis thus applying the bending moment under the desired pressure application of the segments.

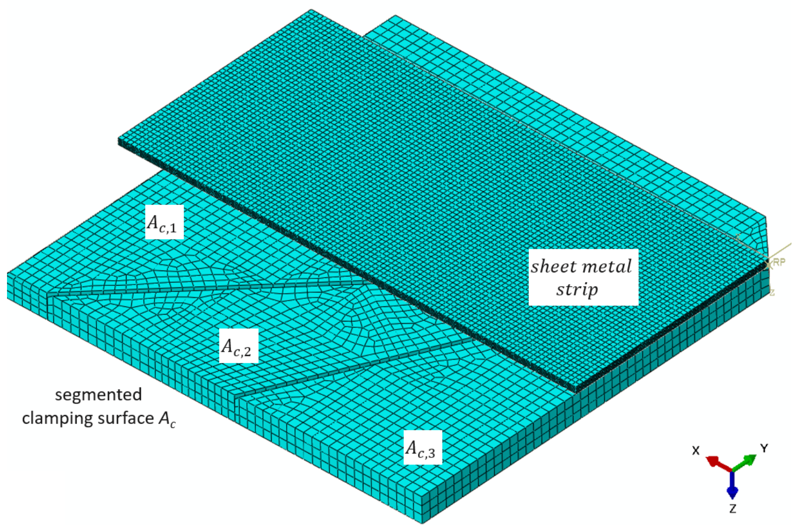

Fig. 4. The FE model of the incremental swivel bending process with segmented tooling concept, here three segments.

In this study, three different cases of contact pressure application were studied and evaluated with respect to the resulting forming zone. Firstly, a process operation with static application of load on each segment throughout the bending process is implemented in the FE simulation model. Next, dynamic operations of the segments were investigated. Either the inner segments are initially unloaded when the bending process initiates and loaded at a defined process point or, vice versa, they are loaded in the beginning and unloaded at a distinct instance of progress. It was shown in analytical considerations, that the forming zone of the in-plane bending process under frictional engagement expands in an angular way and reaches well within the clamping surfaces. Moreover, the forming zone angle γ would be significantly larger than the bending angle propagated by the clamping tools δ. In fact, γ would increase rapidly over the bending progression until reaching a certain threshold angle which is dictated by the tool geometry – here, $\gamma_{ult}/2$ is 45 ° when using quadratic tools. Therefore, the herein studied dynamic loading and unloading operations of the tool segments are operated in relation to the instance where γ reaches its threshold γ_{ult}.

Results

The herein suggested tooling concept would allow to restrict the forming zone to a prescribed angular value smaller than the ultimate forming zone angle γ_{ult} which is given by the tool geometry according to Eq. 6. Considering the unloaded bending angle δ_u according to Eq. 8 which depends on strain resulting from the bending angle δ and the forming zone γ as given in Eq. 7, the analytical consideration evidently shows the potential to limit elastic springback in incremental bending with the herein presented tooling concept, see Fig. 5 left.

According to Eq. 10, strain resulting from the incremental sequence is calculated. From the analytical equations, it is evident that larger strain results from a narrower forming zone angle. In turn, a lesser number of forming zones would overlap each other with such a tighter configuration (as given by superposition *SP*). Hence, in the range of forming fewer but more intense bending increments (i.e., lower values for *SP*), a potential to reduce overall strain in incremental bending is seen in the analytical consideration, cf. Fig. 5 right. Interestingly, a reduction of longitudinal strain in the incremental sequence is only seen for the first segmentation, i.e. from 45° to 22.5°. So far, these considerations only concern the static operation mode of the novel tooling concept, where the tool segments stay active or inactive throughout the bending process.

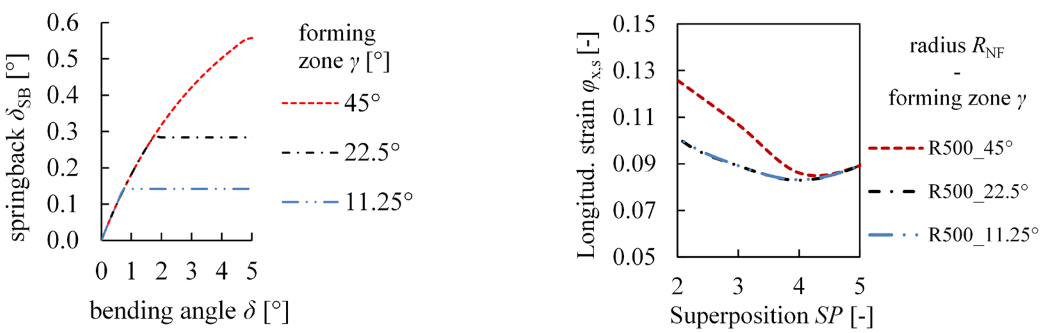

Fig. 5. Elastic springback (left) and strain resulting from bending a defined representative bending radius of 500 mm (right), both as a function of prescribed forming zone angles (45°, 22.5° and 11.25°). It is demonstrated based on analytical considerations, that the novel tooling concept potentially helps to limit elastic springback and strain in incremental bending.

With the help of the numerical process model, the dynamic operation of the segmented tool concept is simulated with the aim to evaluate the influence of an active loading or unloading of those tool segments which are in active contact with the forming zone. In Fig. 6 the numerical setup and the resulting strain maps are plotted for the three different process operations suggested in this paper for the segmented tool concept. In detail, a static operation of the tool concept is studied in simulation as well as a dynamic loading and unloading. The innermost segments are loaded/unloaded b) before, c) during or d) after the forming zone reaches its final angular extension γ_{ult}, respectively. All plots are extracted for the configuration at 0.2 seconds.

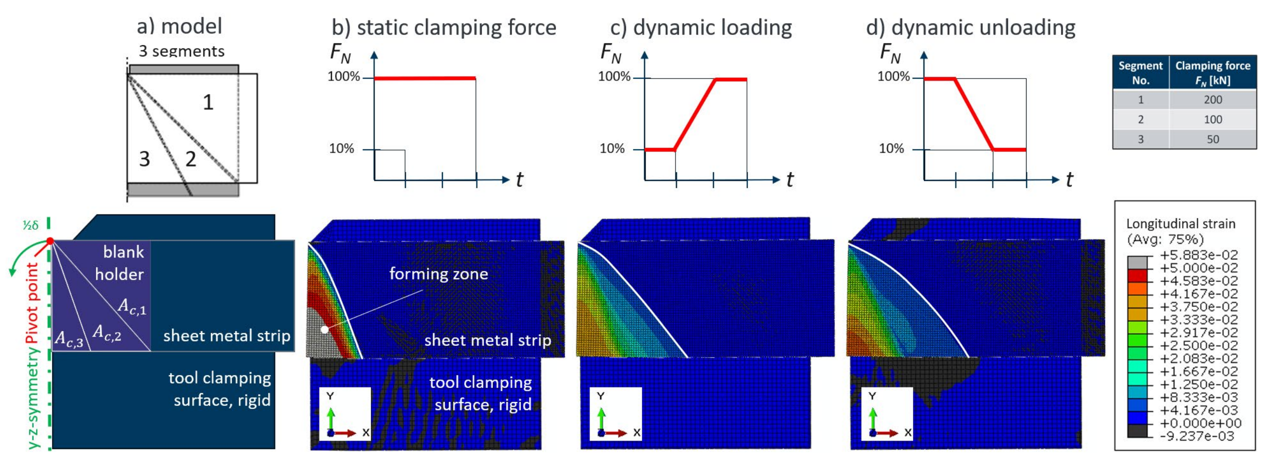

Fig. 6. Study on the evolution of forming zone by means of longitudinal strain with various static and dynamic concepts of tool operation. a) tool concept with three segments, b) static operation with the foremost segments under static load application, c) dynamic concept with the foremost segments being idle initially and loaded at δ = 2°, d) dynamic unloading of the foremost segments at δ = 2°. All plots contain a symmetry plane in the centre of the process.

From these simulation plots, evidently the static operation mode of segments is capable to keep the forming zone at a very narrow extension angle γ, which corresponds to the geometry of the foremost segment, i.e. 22.5° in this case. This concept has been presented in [16] however besides the option to restrict the forming zone, it delivers strong strain gradients and high maximum strain values (b). Evidently from the figure, the dynamic operation concepts deliver smoother strain transitions and softer strain maxima (c, d). By qualitative means, the dynamic loading concept initially lets the forming zone stretch out freely and then imposes a stronger straining in the central area after triggering the innermost segments (c). The dynamic unloading concept (d) delivers an intensely strained area in the central region since it operates during the first few degrees of bending like the static concept (b). However, after triggering the release of the innermost segments of concept (d), the forming zone is allowed to extend towards its final angle γ_{ult}, which results in an outer area of the forming zone that is much strained only weakly.

Conclusion

Advantages are predicted for the dynamic unloading concept, cf. Fig. 6 (d), since it initially plasticizes the sheet metal material sufficiently over the whole width h_0 but applies only limited strain values over the whole bending progression. In detail, the resulting forming zone is divided into two distinct areas, the inner area (the yield sheath) of higher strain application that develops during the loaded condition of the innermost segments, and the outer area that develops after unloading these segments. Two benefits might result in practical application: Firstly, the initial plasticizing helps to prevent uneven release of residual stress in springback, which results from a pronounced elastic deformation area in the central region of the forming operation. Undesired shape deviations are observed in practical experiments (twisting, buckling).

Moreover, this interpretation well agrees with the analytical calculations, see Fig. 5 left, which also predict reduced springback for narrower forming zone angles. Secondly, in an incremental process operation, the superposition of the outer area of the forming zone obtained from the dynamic unloading tool concept leads to fewer accumulation of strain from multiple forming zones. Failure due to cracking might be prevented from this concept. Again, this observation is confirmed by the analytical predictions, cf. Fig. 5 right, which suggest lower strain values for more narrow forming zones). However, besides the efforts in building such a tool in practice and the accompanying process control, such an operation might lead to pronounced coarseness of the bending geometry.

In practice, such a segmented tool concept would require a very high energy density to apply the desired contact pressure on relatively thin segments. Herein, we suggest hydraulics to actuate the individual tool segments like multi point forming [20]. Using the developed FE-model, the necessary segment forces might be studied in further approaches to define the minimum necessary load to achieve a process operation as suggested in the present work. As is, indeed considerable process forces are necessary on small tool segments which require high pressure hydraulic systems. Alternative tool concepts besides hydraulics are still under consideration by the authors.

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