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Numerical Investigation and Optimization of Blank-Holder and Magnetorheological Actuators Configurations for Deep Drawing Objectives

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Abstract. This study investigates the structural response of blank-holders (BHs) equipped with spatially distributed magnetorheological (MR) actuators for adaptive deep drawing. While MR actuators provide fast, independent, and high-resolution force modulation, their effectiveness depends critically on the BH's ability to transmit spatially differentiated loads without excessive diffusion or unrealistic stress localization. The relationships between BH stiffness, actuator spacing, and pressure localization at the sheet interface remain only partially understood, limiting the implementation of distributed blank-holding strategies. To address this gap, a comprehensive finite element (FE) framework is developed, combining a full closed-cup deep-drawing model with a complementary simplified configuration that isolates local deformation mechanisms under single-actuator loading. Parametric analyses examine the influence of BH thickness, local actuator force, and actuator spacing on stress distribution, localization radius, and overlap between adjacent load paths. Results show that BH thickness is the dominant factor governing spatial resolution: thinner BHs enable sharp pressure localization, whereas thicker ones diffuse local loads and suppress stress peaks. The spacing between actuators must therefore be selected as a function of BH stiffness to avoid stress-free regions while preserving distinct pressure footprints. For the reference industrial configuration (60 mm BH thickness), an actuator spacing of approximately 150 mm achieves the optimal compromise between localization capability and continuous sheet support. The proposed framework establishes quantitative design criteria for BH geometries compatible with MR-based adaptive forming and supports the development of next-generation blank-holding systems offering enhanced process stability, reduced scrap, and improved material-flow control.

Introduction

Deep drawing is a widely used sheet-metal forming process whose robustness depends on the controlled flow of material under variable friction, geometry, and mechanical properties [1]. The blank-holder (BH) plays a central role by stabilizing the flange, preventing defects, and regulating in-plane strain distribution. Conventional BH systems apply a global, uniformly distributed blank retracting force, which ensures process simplicity but offers limited capability to address local variations on blank draw-in arising from anisotropic material behaviour, uneven lubrication, or complex part geometries.

Recent high-dynamic actuation technologies, particularly magnetorheological (MR) actuators [2], enable pressure profiles that vary around the BH circumference both spatially and temporally. Despite this progress, the interaction between BH stiffness, actuator spacing, and the level of pressure localization achievable at the sheet interface remains insufficiently understood [3], therefore the full capability of MR actuators is limited. This study addresses these gaps through a systematic finite element (FE) investigation [4] of deep-drawing processes equipped with spatially distributed MR actuation.

Traditional BHs, typically designed as thick and rigid plates, ensure structural stability [5] but inherently suppress local adjustments of pressure, an increasingly important capability in adaptive forming, damage mitigation, and scrap reduction. Existing BH solutions provide only partial spatial control. Segmented BHs [6] introduce local actuation but require complex assemblies and may create contact discontinuities [7]. Shaped BHs compensate pressure profiles through geometry but lack adaptability [8]. Mechanical spring-based [9] and nitrogen gas spring-based [10] systems add compliance but offer poor controllability [11], while hydraulic units generally operate with limited spatial resolution [12]. As a result, current industrial BHs cannot fully exploit modern actuation strategies requiring fast, high-resolution adjustments [13].

MR actuators overcome many of these limitations [14]. As shown by Simonetto et al. [2], they use MR fluids [15] whose rheological properties change under a magnetic field, enabling compact, fast-responding devices capable of independently modulating force across dense arrays [16]. These characteristics make them promising for distributed blank-holding, provided that the BH structure itself supports the transmission of spatially distinct loads [17]. Excessively rigid BHs diffuse local actuation effects, while overly compliant ones compromise global stiffness and can generate excessive pressure peaks. Effective distributed forming therefore requires a carefully balanced BH design.

The present study examines how BH thickness influences pressure localization, how actuator spacing affects interaction between adjacent load paths, and how these mechanisms can guide the design of BH geometries suited for MR-based distributed forming. Through detailed FE simulations, a unified framework is developed linking BH stiffness, actuator layout, and applied forces to the resulting pressure distribution on the sheet, supporting next-generation adaptive blank-holding strategies.

Magnetorheologic Actuator

Magnetorheological actuators enable precise control of force–stroke curves, including configurations in which the available force decreases monotonically with increasing stroke. This response is tuned by regulating the magnetic field applied to the MR fluid, which is achieved by modulating the current in the internal coils through a dedicated power transformer. When activated, ferromagnetic particles within the fluid align with the magnetic field, increasing both viscosity and yield stress. By adjusting the field intensity, the actuator can rapidly transition between low-resistance and high-resistance states, enabling highly responsive, real-time force control suitable for distributed blank-holding applications.

Fig. 1a shows a longitudinal section of the actuator, illustrating its internal components and pressure zones, while Fig. 1b presents an example of a decreasing force-stroke curve and the corresponding current profile required to generate it. By knowing the pressures values and their application surfaces, it is possible to evaluate the damping force of the actuator:

$$F = P_{in}A_1 + P_{pr}(A_1 + A_3 - A_2). \quad (1)$$

Where P_{in} is the MR-fluid pressure, consisting of the magnetic-resistance component activated by the applied current and the viscous component associated with fluid motion, P_{pr} instead, is the preload pressure of the nitrogen gas, needed for compensate the volume of the piston rod entering the cylinder during the stroke.

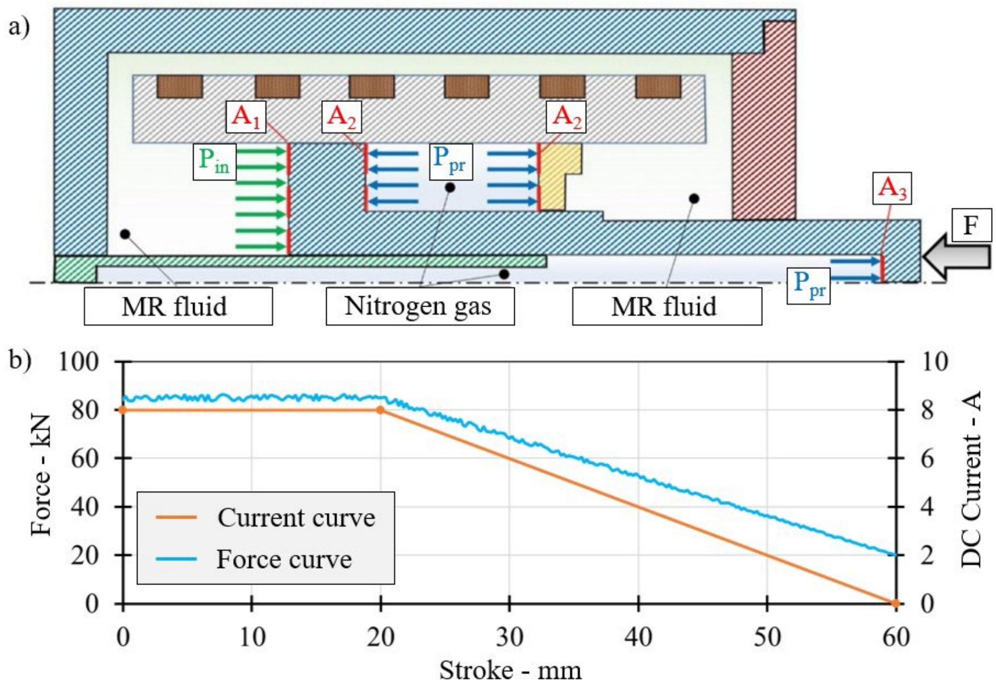

Fig. 1. a) Section of the MR actuator; b) Example of force and current curve of the MR actuator along the stroke of the piston.

Therefore, the effectiveness of MR-based local actuation depends on the BH's ability to maintain spatially distinct load paths. When the BH is too rigid, localized forces are spread over a wide contact region, suppressing pressure peaks and reducing spatial resolution. Conversely, a BH that is too compliant may produce excessive localization, leading to unrealistic stress concentrations and reduced global support.

Numerical Framework

A comprehensive FE simulation campaign was carried out to study the blank-holder plate structural elastic behaviour under localized loading. The numerical model reproduces the deep drawing of a closed-cup geometry (Fig. 2a) made of DC04 steel using an industrial tooling configuration. A complementary simplified model (Fig. 2c), involving only a single actuator, is included to isolate local deformation mechanisms.

The 0.7 mm thick sheet is modeled using shell elements with an elastic-plastic constitutive law calibrated for DC04 steel (Fig. 2b). The material parameters adopted are: Young's modulus $E = 210$, Poisson's ratio $\nu = 0.3$, initial yield stress $\sigma_{y0} \approx 170$ MPa, and an isotropic hardening law described by a Hollomon-type relationship $\sigma = K\varepsilon^n$ with K=525 MPa and n = 0.22. The blank-holder plate is represented by three-dimensional solid elements, enabling evaluation of through-thickness stress gradients and the influence of BH thickness on compliance, i.e., its tendency to deform elastically under applied loads. The blank-holder and tools are modeled as made of tool steel with linear-elastic behavior, using a Young's modulus $E = 210$ GPa as stiffness is primarily governed by their elastic properties. Actuators are implemented as independent vertical solid elements applying controlled normal loads to the BH surface according to Fig. 2, replicating the action of MR units. Contact interactions between sheet, BH, and die include frictional effects, ensuring realistic draw-in and pressure development. Boundary conditions reflect the industrial die-BH-punch configuration.

Two key structural parameters were systematically varied: the blank-holder (BH) thickness, which determines its elastic stiffness (or, inversely, its structural compliance) under loading; and the actuator spacing.

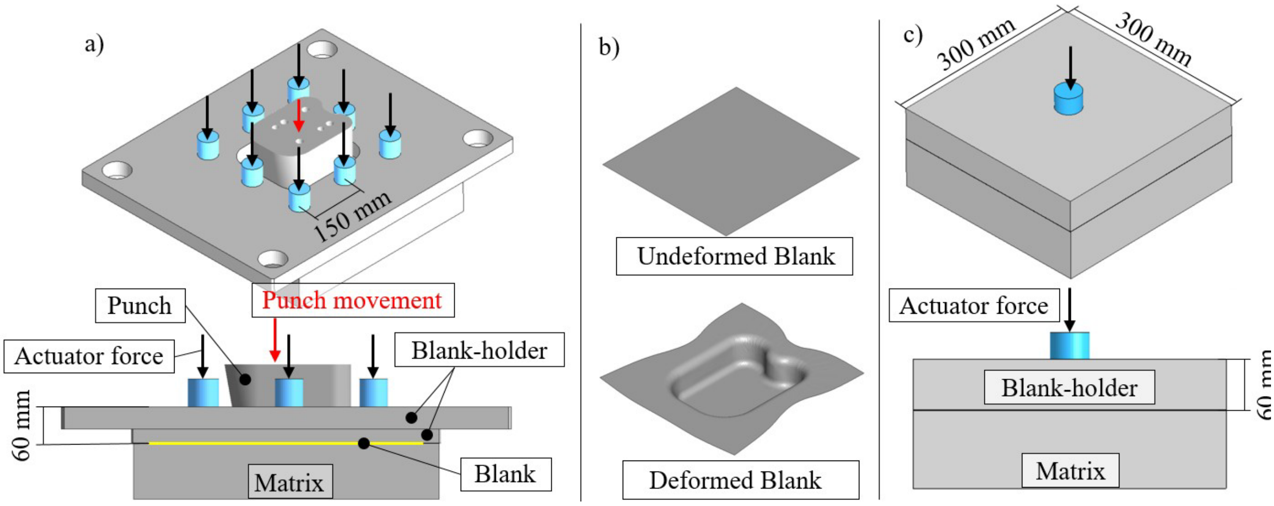

Fig. 2. a) Numerical model of a closed-cup geometry; b) Closed-cup blank before and after the forming process; c) Simplified model of one single MR actuator.

The latter controls the spatial density of force application, ranging from closely spaced, high-density layouts to widely spaced, low-density configurations. Furthermore, multiple force levels were applied to evaluate their effects on the resulting stress distributions and contact pressure fields.

Performed numerical valuation focuses on both local and global indicators of BH behaviour. Stress distributions through the blank-holder thickness, modeled as a thick plate, are used to assess whether the structural response is dominated by bending or transverse shear deformation. The contact pressure distribution at the BH-sheet interface characterizes the magnitude and spatial extent of load transfer. The degree of superposition between pressure distributions generated by adjacent actuators provides a measure of actuator interaction and the effective spatial resolution of force control. Peak contact pressures and the depth of stress penetration into the blank-holder thickness offer further insight into the structural sensitivity to localized loading.

Summarizing, these metrics describe how BH geometry and actuator arrangement influence the transmission and redistribution of localized loads. The modeling framework captures the interplay between local elastic deformability and overall structural stiffness, offering a valid design for blank-holders compatible with MR-based distributed forming systems.

Single cylinder model: local effects

Force variation. Before examining the influence of blank-holder thickness and actuator spacing, it is necessary to first assess the effect of the applied actuator force itself and to evaluate how variations in this force modify the stress state within the system.

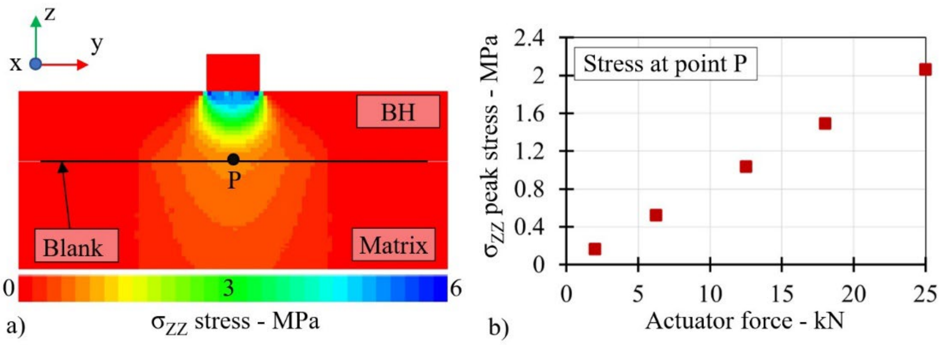

Fig. 3. a) Stress distribution σ_{ZZ} in the middle section of the single cylinder model with a cylinder force of 12.5 kN; b) σ_{ZZ} peak stress vs. Actuator force measured at point P.

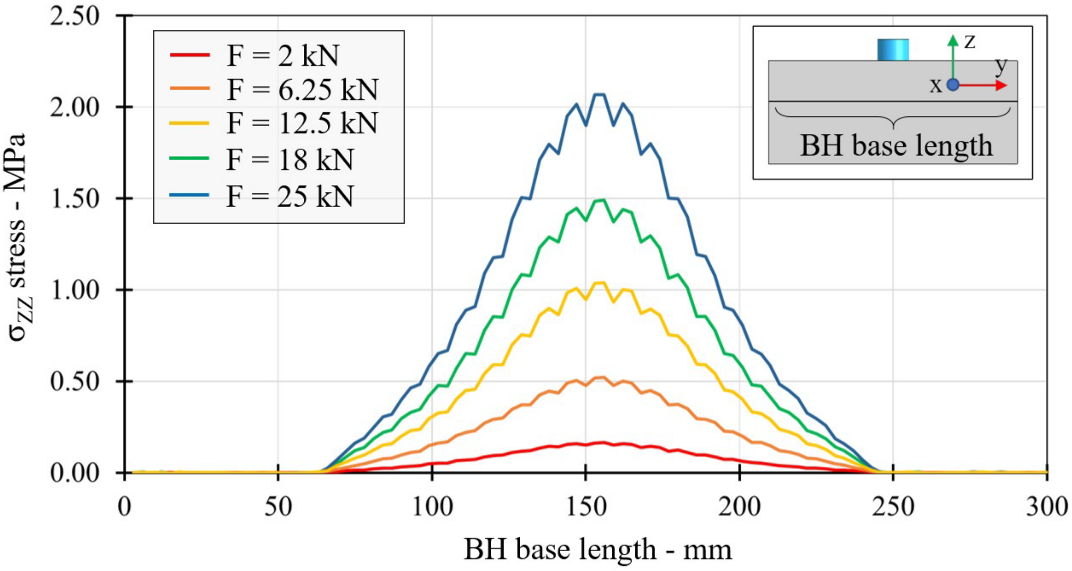

Fig. 4. σ_{ZZ} component at the base of the blank-holder for different force values applied to the cylinder; BH thickness of 60 mm.

To isolate this phenomenon, the simplified numerical model containing a single actuator is particularly useful, as it allows direct observation of the stress response under different applied force levels. Fig. 3a shows the stress distribution on a representative section of the simplified model for a cylinder force of 12.5 kN, in which the blank-holder plate thickness corresponds to that of the industrial closed-geometry tool (60 mm). Fig. 3b reports the peak stress component in the direction normal to the blank-holder surface (σ_{ZZ}) for the various applied force levels. As expected, the peak stress at point P increases linearly with the amount of the force applied by the actuator, confirming the proportional relationship between local loading and the resulting stress concentration.

Another relevant aspect in evaluating the effect of varying actuator force is determining the spatial extent of the stress field at the base of the blank-holder. Understanding how far the stress propagates laterally is essential, as it provides insight into whether the applied force influences the minimum spacing required between adjacent actuators. Fig. 4 presents the σ_{ZZ} component measured at the lower surface of the blank-holder. The results show that the extent of the stress distribution remains essentially unchanged as the applied actuator force increases. Although the magnitude of the stress scales with the imposed load, its lateral spread is largely unaffected. This behaviour indicates that the force level does not govern the spatial reach of the stress field and therefore does not influence the criteria for actuator spacing in the BH design.

From these observations, it can be concluded that the applied force affects only the intensity of the local stress but not its distribution radius. Consequently, actuator spacing must be defined primarily by geometric and stiffness-related parameters rather than by the magnitude of the force delivered by each actuator.

Thickness variation. Another key parameter that can be effectively examined through the simplified numerical model is the blank-holder thickness. This parameter is particularly influential because it governs the degree of stress localization beneath the actuators, independently of the applied force, as demonstrated in the previous section. Within this framework, five different blank-holder thicknesses were investigated, all defined as multiples or fractions of the reference industrial thickness of 60 mm: (i) 15 mm; (ii) 30 mm; (iii) 60 mm; (iv) 90 mm and (v) 120 mm. Fig. 5 reports the σ_{ZZ} stress profiles at the lower surface of the blank-holder for the various thickness configurations. Calculated results clearly illustrate that reducing the blank-holder thickness increases the peak stress transmitted to the sheet while simultaneously narrowing the lateral spread of the stress field. In other words, a thinner blank-holder exhibits higher local elastic deformability, allowing the applied load to concentrate more strongly beneath the actuator and confining its influence to a smaller region.

Conversely, increasing the blank-holder thickness leads to a more uniform distribution of stress over a wider area and a reduction in the peak stress value. A thicker plate behaves as a stiffer structural component, diffusing localized loads more effectively and thereby attenuating the degree of pressure localization. This behaviour is consistent with classical plate theory, where bending stiffness scales with the cube of the thickness; even modest increases in thickness therefore produce substantial reductions in local deformation. These observations confirm that BH thickness is the dominant structural parameter controlling stress localization and, consequently, the achievable spatial resolution in distributed blank-holding systems. Understanding this relationship is essential for designing blank-holder plates capable of transmitting spatially differentiated pressures without compromising global stiffness or formability robustness.

To clarify the influence of blank-holder thickness on the appropriate spacing between adjacent actuators, which will be examined in detail in the following section, Fig. 6 presents the distribution diameters *D* of the σ_{ZZ} stress distribution extention at the lower surface of the blank-holder for the various thickness configurations. The results reveal an approximately linear increase of *D* with increasing blank-holder thickness, although the trend gradually approaches an asymptotic upper limit of roughly 250 mm (even with a BH thickness of 150 mm the *D* value is ≈ 250 mm). This saturation indicates that beyond a certain stiffness level, further increases in blank-holder thickness provide diminishing contributions to the lateral spread of the transmitted load.

From these observations, when temporarily disregarding the more complex interactions occurring during forming, namely those between the blank-holder and the blank, the blank and the die, and the blank and the punch, a first approximation of the ideal actuator spacing can be established. For a given blank-holder thickness, the recommended spacing between two consecutive actuators should match the corresponding stress-distribution diameter *D* at the BH base. Such spacing ensures that no regions of zero stress arise at the sheet-BH interface (which would occur if spacing exceeded *D*, making local control of material flow impossible in that areas), while also preventing excessive overlap of adjacent pressure fields (which would occur if actuator spacing are chosen smaller than *D* and would negate the benefits of spatially differentiated pressure control). This relationship provides a preliminary geometric criterion for designing actuator arrays capable of maintaining effective spatial resolution in MR-based distributed blank-holding systems.

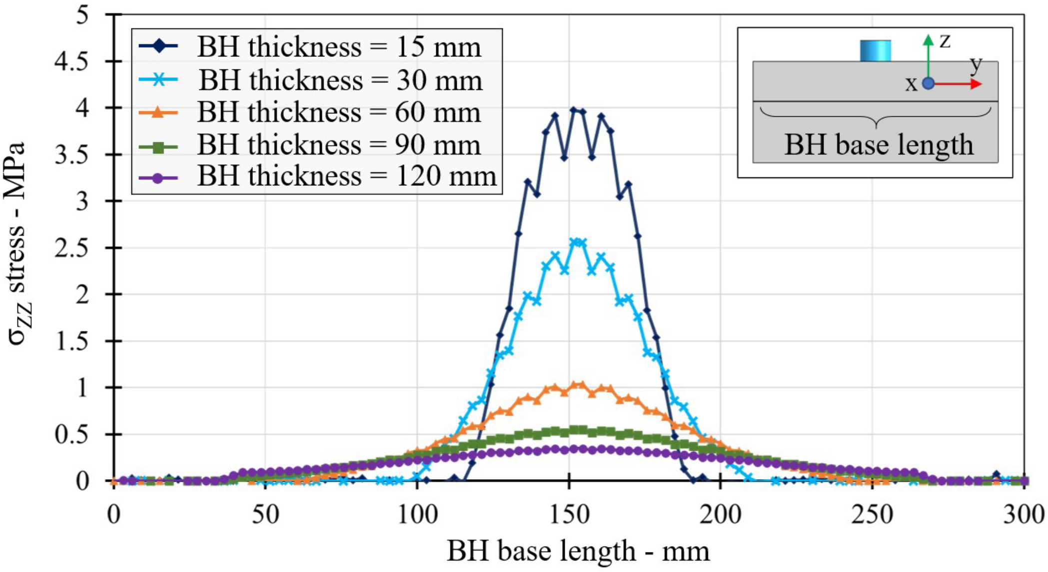

Fig. 5. σ_{ZZ} distribution at the BH base for different plate thicknesses.

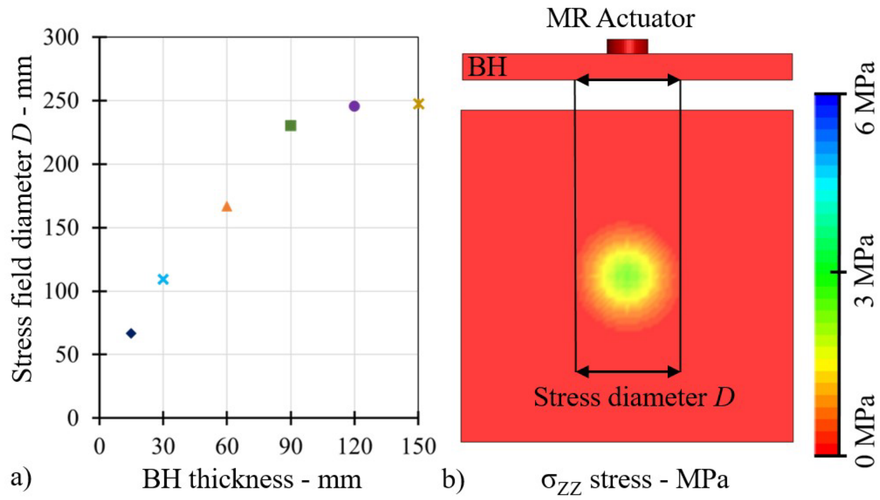

Fig. 6. a) Stress field diameter D vs. BH thickness in the single cylinder numerical model; b) σ_{ZZ} distribution at the BH base for a 12.5 kN load and 30 mm BH-thickness.

A more comprehensive discussion of thickness and spacing effects, considering the full closed-cup geometry and therefore the complete numerical model, follows in the next section. There, the influence of blank-tool interactions on optimal actuator placement and blank-holder design is addressed, offering a more realistic basis for industrial implementation.

Closed Geometry Global Effects

Thickness variation. As in the previous section, several blank-holder thickness configurations were examined, this time applied to the full deep drawing process of the closed-cup geometry illustrated in Fig. 2a. Unlike the simplified model, by which the sheet is merely compressed between the BH and the die, in the full geometry of the drawing die, the sheet undergoes significant deformation as it is drawn into the cavity by the punch. The evolving motion of the sheet during forming alters the characteristics of the sheet-BH interface, introducing effects that were not present in the simplified configuration. These differences lead to results that deviate slightly from the conclusions previously obtained, and therefore warrant a dedicated discussion.

Fig. 7 shows the distributions of interface stresses between the sheet and the blank-holder for the various thicknesses with the load on cylinders equal to 12.5 kN. The overall trend remains consistent with the findings from the simplified model: thinner blank-holder plates do promote stronger localization of the applied load, whereas increasing thickness spreads the pressure more uniformly across the contact surface.

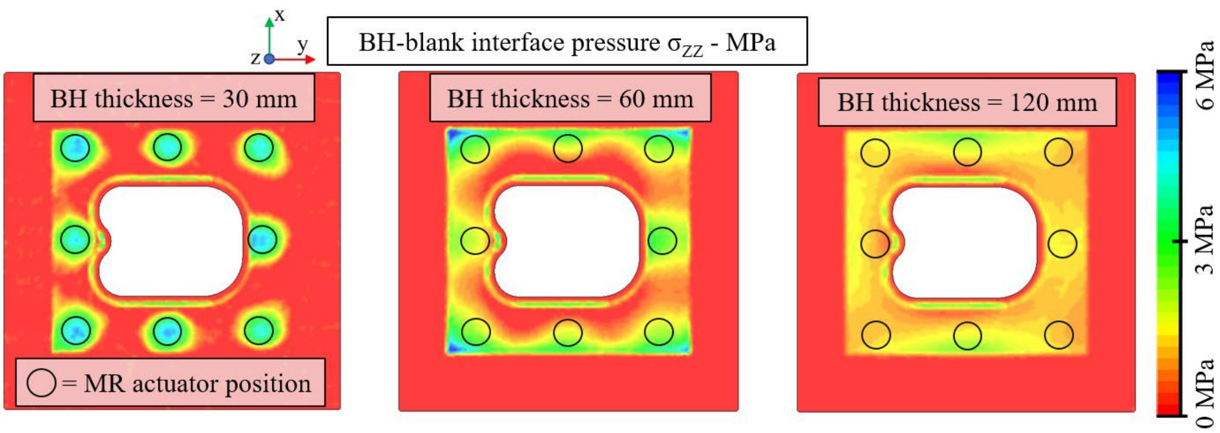

Fig. 7. σ_{ZZ} distribution at the interface between blank and BH for three different BH plate thicknesses; applied force: 12.5 kN each.

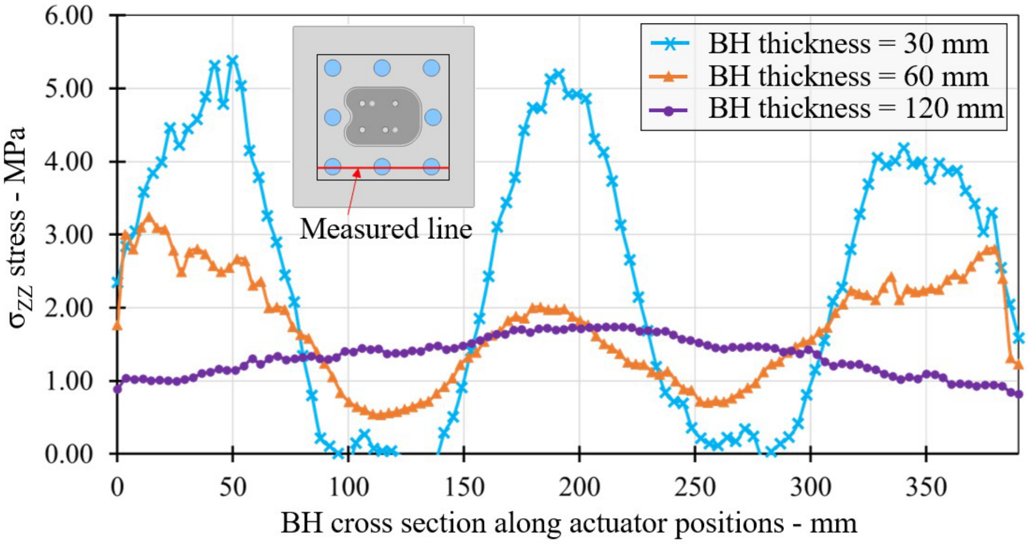

Fig. 8. σ_{ZZ} vs. actuator location for three different BH thickness

However, the additional motion of the sheet introduces new gradients and interactions that modify the shape and symmetry of the resulting pressure fields.

Fig. 8 reports the σ_{ZZ} stress component along a line passing through three consecutive actuators. Again, a highly localized stress field with pronounced peaks is observed for a thickness of 30 mm, while a nearly homogeneous stress distribution characterizes the 120 mm configuration. For the reference thickness of 60 mm, the stress fields of adjacent actuators exhibit a mild overlap in the regions midway between two cylinders, confirming that the original spacing of 150 mm provides an adequate level of localization without generating stress-free zones. This indicates that the original structural layout already meets the criteria for spatially resolved actuation. A closer inspection of the 60 mm pressure distribution reveals that the stress peaks beneath the three actuators are not perfectly uniform. Owing to the blank's motion and deformation during the drawing process, the outer actuators generate slightly higher stress peaks than the central one, introducing a measurable asymmetry in the stress distribution. This effect highlights the influence of the evolving sheet geometry on load transmission and underscores the importance of accounting for forming-induced kinematics when defining design guidelines based on simplified models. The observed asymmetry originates from the fact that the sheet does not undergo a uniform displacement during the drawing process. As the material flows toward the die cavity, different zones do experience more pronounced draw-in, increased local bending, and locally higher frictional resistance. These effects increase the reaction forces transmitted to the outer actuators, leading them to develop slightly higher stress peaks than the central one and ultimately producing the measured imbalance in the pressure field.

Inter-cylinder space variation. Building on the considerations developed in the previous sections, it is now possible to define the ideal actuator spacing for an efficient blank-holder design. The analyses presented here do refer to the reference blank-holder thickness of 60 mm; for other plate thicknesses, the same reasoning can be directly extended by adopting the corresponding ideal spacing value D shown in Fig. 6a.

To investigate the influence of actuator spacing, three distances were examined: 120 mm, 150 mm, and 180 mm. The value of 150 mm represents the nominally optimal spacing (the simplified-model prediction was approximately 157 mm, but a slightly smaller value was chosen here to avoid the formation of stress-free zones during the actual forming process, in fact, the material in those areas cannot be actively controlled by the actuators, making the local sheet flow ungovernable and significantly increasing the risk of wrinkling).

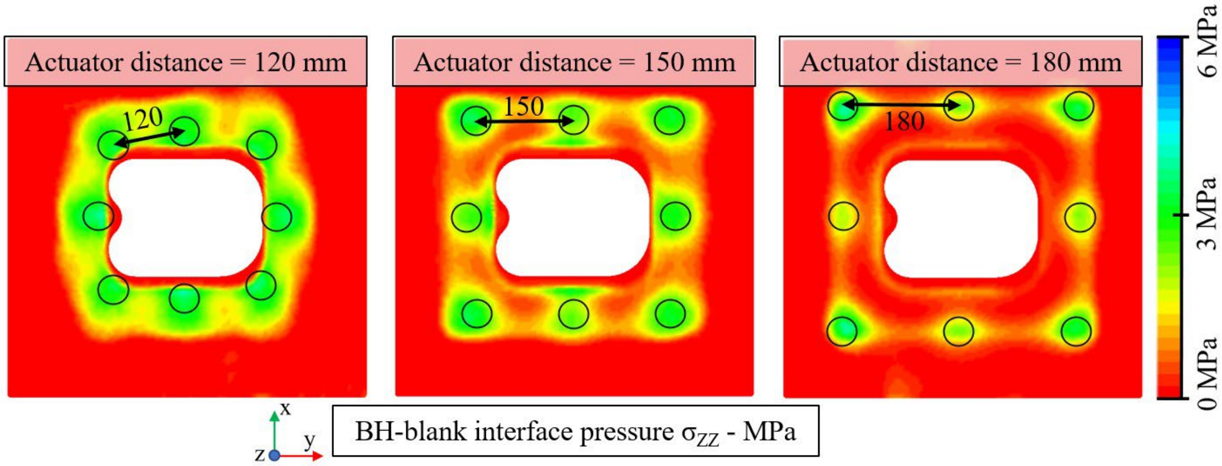

Fig. 9. σ_{ZZ} distribution at the BH base for three different cylinders spacing; cylinder force of 12.5 kN each.

Fig. 9 illustrates the σ_{ZZ}-distributions at the sheet-BH interface for the three spacing configurations. When the spacing is reduced to 120 mm, the pressure fields generated by adjacent actuators overlap extensively, leading to an almost uniform stress distribution across the interface. From Fig. 10 it is possible to observe that the contributions from adjacent actuators, in the 120 mm spacing-case, accumulate in the intermediate regions, effectively producing a summed response. While such homogenization eliminates low-stress zones, it also suppresses the distinct pressure peaks needed for localized control of the material flow. One of the potential benefits of a reduced actuator spacing is the increased control in the bending region, as the actuators are necessarily positioned closer to the die's curvature, but losing all the advantages of spatial differentiation.

At the opposite extreme, a spacing of 180 mm produces a markedly localized response as evident in Fig. 9: the stress peaks beneath each actuator are well separated, and wide regions of low or near-zero stress appear between them. This configuration reduces the effectiveness of distributed blank-holding, since large portions of the flange are left uncontrolled. However, the actual extent of these low-stress areas depends on the blank size. In the early stages of forming, the entire flange still lies under the influence of all eight actuators, meaning that the sheet remains globally supported (but with zero stress zones). Only when the material is drawn inward and portions of the blank move beyond the effective spatial extent of the actuator-induced stress distribution does the risk of insufficient blank-holding increase, leaving segments of the blank edge less controlled and more susceptible to wrinkling or uncontrolled draw-in.

The intermediate spacing of 150 mm offers a balanced condition: individual actuators retain their ability to generate localized pressure peaks, yet the overlap between adjacent stress distribution extensions remains sufficient to avoid unregulated regions; in fact, in this case, the stress profile remains strictly positive along the entire outline, ensuring continuous regulation of the sheet flow. At the same time, the localized peaks directly beneath the actuators remain clearly identifiable, confirming that the system preserves the spatial differentiation required for effective distributed blank-holding. This spacing therefore achieves an optimal balance between maintaining localized actuation effects and preventing uncontrolled regions along the flange.

Moreover, numerical simulations have shown that maintaining a 150 mm spacing and a blank-holder thickness of 60 mm, while differentiating the forces applied by the individual actuators, enables a significantly higher minimum thickness in the formed component (≈ 0.62 mm) compared with the current configuration (≈ 0.57 mm). These results and their implications on advanced actuator positioning strategies will be discussed in detail in future publications.

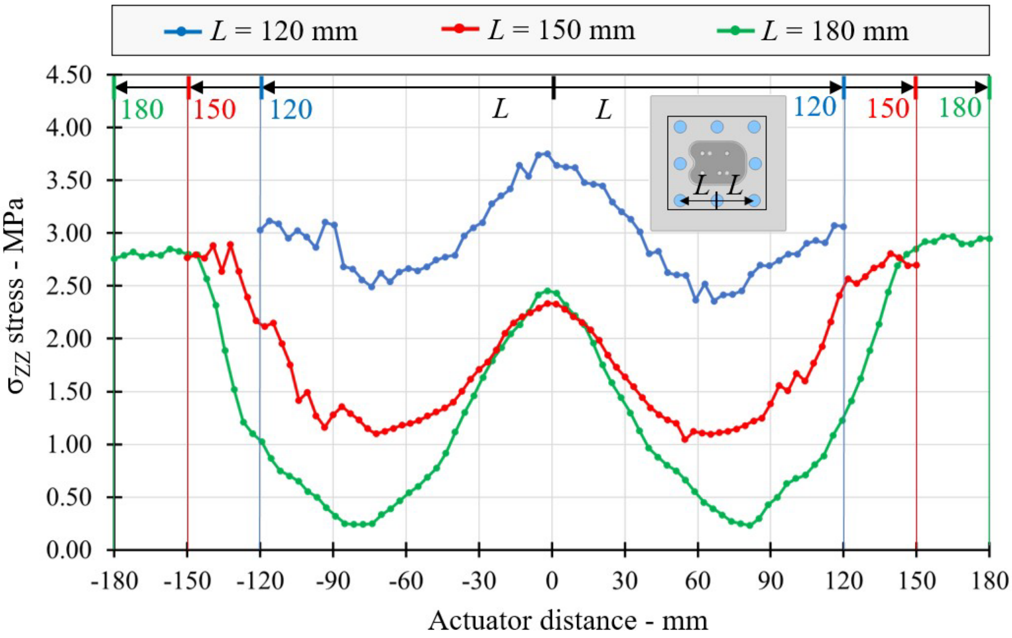

Fig. 10. σ_{ZZ} vs. inter-cylinder distance for three different spacing values

Conclusions

This work provides a systematic investigation of how blank-holder geometry and actuator arrangement influence the transmission of spatially differentiated loads in deep drawing processes employing magnetorheological actuators. Through a combination of simplified and full-geometry FE models, three key findings were elaborated in this contribution: (i) Blank-holder thickness is the primary determinant of stress localization. Thinner BHs exhibit high local elastic deformation, producing strong, narrow pressure peaks beneath each actuator. Increasing thickness diffuses these peaks and reduces their amplitude. The diameter of the stress-affected zone increases approximately linearly with plate thickness of BH and tends toward an upper bound, indicating diminishing benefits for very stiff BHs. (ii) Local actuator force affects peak stress intensity but not the spatial reach of the stress field. The radius of the stress-distribution extension remains essentially unchanged across the examined force range, meaning that actuator spacing should be defined by geometric and stiffness-related parameters rather than by load levels. This decoupling simplifies the design of actuator arrays for MR-based systems. (iii) Actuator spacing governs the balance between spatial resolution and global process control. When spacing is too small, adjacent pressure fields overlap excessively, homogenizing the interface stress and suppressing local actuation effects. When spacing is chosen too large, extensive low-stress regions arise between actuators, reducing control authority and increasing susceptibility to wrinkling. For the reference of 60 mm BH plate thickness, a spacing of 150 mm ensures continuous sheet support while maintaining distinct localized pressure peaks.

Overall, the study establishes a unified framework linking BH stiffness, actuator spacing, and localized loading behavior, offering practical guidelines for designing blank-holders that fully exploit the capabilities of MR actuators. The results demonstrate that effective distributed blank-holding requires an intermediate level of BH stiffness and an actuator pitch tailored to the thickness-dependent stress-distribution diameter. These findings provide the structural foundations for advanced adaptive forming technologies, enabling improved robustness, reduced material waste, and enhanced control of in-plane deformation during deep drawing.

Future work will extend the present structural analysis toward fully coupled process simulations including material plasticity, contact evolution, and real-time control strategies. Experimental validation under industrially representative conditions will be essential to quantify the robustness of the findings against parameter variability and to assess long-term reliability of MR actuators.

In industrial application a key advantage of MR actuators is their capability to dynamically adapt the applied force in response to process variability (e.g., changes in lubrication), thereby enhancing robustness under real production conditions. Future developments may involve the integration of AI-based control systems, such as neural networks trained on real-time process parameters (e.g., sheet draw-in), which represents both a promising opportunity and a technological challenge for industrial implementation.

Acknowledgments

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