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Adaptive metal flow control in stamping through ferrofluidic actuators

Enrico Simonetto[a], Andrea Ghiotti (1)[a,*], Michele Brun[a], Stefania Bruschi (1)[a], Stefano Filippi[b]

[a] *Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131, Padova, Italy*
[b] *MSD S.r.l., via Vittorio Veneto 21, 34170, Gorizia, Italy*

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ABSTRACT

Inhomogeneous metal flow in stamping non-axisymmetric parts makes material deformation in the flange critical, resulting in uneven sheet thickness distribution, high blank holder forces or even the need to use draw beads to compensate for large material draw-in. The paper presents an innovative mechatronic system for the adaptive control of the blank holder force, which integrates ferrofluidic actuators and non-contact sensors for the in-line material flow measurement, with the aim of exploring, through laboratory-scale experiments, the feasibility of its implementation in stamping processes and understanding the potential benefits to enable more reliable process design.

1. Introduction

Despite the significant advancements in sheet metal forming design due to the increased availability of numerical tools (i.e. 3D modelling, FEA etc.), the accuracy and reliability of numerous stamping processes still depend on the variability of blank properties and process parameters [1]. Additionally, a rising demand in all consumer markets for highly customized products is driving manufacturing production towards smaller batches, frequent tool changes, and greater process flexibility. Thus, for the stamping industry, it is becoming essential to implement in-line control techniques for rapid die setups and real-time adaptivity to wider process parameter windows [2].

In recent years, the development of control systems for deep drawing processes has had a major impact on the blank holder (BH), which is responsible for regulating the material flow by holding the flange during forming. The evolution from rigid to flexible [3] or segmented BH designs [4] has led to the rapid development of both actuation and sensing approaches to enable increasingly precise setting of process parameters such as blank holder force (BHF), lubrication and dies/machines deflections.

As attractive as the idea of adaptive dies may seem, actuation devices for secondary die movements in sheet metal stamping are still underperforming or too expensive given the benefits they offer. Coil springs, being elastic devices that store mechanical potential energy when compressed, cannot be used for stroke control purposes, and are recommended for use only in case of low BHFs or when die space is limited [5]. Nitrogen gas springs are the most widely used solution for applying the required BHF to the flange, given their ease of use and low price. However, they suffer from well-known limitations such as the possibility to apply only increasing forces along the working stroke, the almost total lack of pressure control and, no less important, the critical safety issues in the event of seizure or jamming of the dies [6]. Servo-hydraulic cushions offer advanced control of die movements and are often integrated directly into the stamping press. However, this solution requires the oversizing of the machine systems, which may not be economically viable, and is affected by fluid elasticity and long response times due to their electronics [7]. Active draw beads [8] and piezoelectric actuators were used in [9] to control the pressure in different zones of segmented BH, proving some advantages in defects control but they suffer from dramatically limited working strokes.

Concerning process monitoring, recent developments in sensing and machine to machine (M2M) communication protocols have made it possible to record ever-increasing amount of process data, which has affected all levels of both machines and tools. The greatest advances have been made in force and material flow measurements using contact [10], non-contact [11], or optical sensing techniques [12]. As a result, the need for a deeper understanding of the process itself has grown dramatically, potentially leading to a more complex and time-consuming process design phase. Despite the potential for process knowledge, the main limitations appear to be the high technical complexity and the related costs of adequate automation, often aggravated by difficulties in integrating with existing monitoring systems.

In this framework, the paper presents a new mechatronic system for simple and self-adaptive metal flow control in stamping. At the heart of the approach there is a new family of ferrofluid-based actuators, which allows for extreme flexibility in the BH design and BHF application, and consequently, metal flow control that is particularly critical for complex shapes. The first part presents the general architecture of the system, showing a high potential integration with numerical simulation tools the process design. The second part reports the main information of the new mechatronic system, composed of ferrofluidic actuators, non-contact laser optical sensors

* Corresponding author.
E-mail address: andrea.ghiotti@unipd.it (A. Ghiotti).

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embedded in the dies, and the algorithms to optimize the metal flow in deep drawing. Finally, the system was validated on a small-scale deep drawing of a hat-shaped profile, demonstrating good capabilities in controlling metal flow and improving geometric accuracy in stamped parts.

2. Approach

Process parameters often present a large scatter, which limits the advantages of FEA design and forces engineers into time-consuming and costly adjustment procedures. With this in mind, the goal is to provide a self-adaptive system capable of compensating for unexpected material flow variations and giving extreme flexibility in controlling the BHF or even the local pressure in the case of segmented BH. The main innovation is represented by the ferrofluidic actuator (patent pending [13]), whose advantages consist in (i) fully controllable force along the entire working stroke, (ii) extremely fast dynamic response (typically shorter than hydraulic servo valves), and (iii) high energy efficiency due to the reversible behaviour, which allows limiting their activation only when necessary during the single stroke.

Initial FE analysis is used to calculate the metal sheet deformation, forming loads and optimal BH pressure distribution. These parameters are inputs to the control algorithm, which sets the proper force for each actuator and elaborates feedback signals about local material flow from non-contact sensors embedded in the die. Then, the force applied by each actuator is corrected in real-time against the theoretically expected metal flow. Unlike complex force or pressure measurements, which may be influenced by local deflections, non-constant friction values, etc., the key parameter of the proposed optimization approach becomes the direct measurement of the metal flow under the BH, making control simple and reliable.

3. The mechatronic system

The mechatronic system consist of (i) a set of innovative ferrofluidic actuators, (ii) non-contact sensors for in-line material flow measurement, and (iii) a control algorithm as detailed below.

3.1. Ferrofluidic actuation

Compared to conventional ferrofluidic single-end actuators which are characterized by a magnetic circuit embedded in the piston [7], the innovative design features a sleeve between the piston and barrel. This sleeve incorporates a stator winding excited in DC, which allows for a longer ferrofluid activation length than the entire operational stroke of the actuator. The activation length is more than 4 times the height of the piston. This design has made it possible to meet the force and size requirements of the ISO11901 standard for gas springs [14]. Fig. 1(a) shows a longitudinal section of the device with detail of the annular gap along which the ferrofluid flows. The inner rod has been designed to improve lateral stiffness and to avoid possible misalignments due to lateral loading in the process. At the

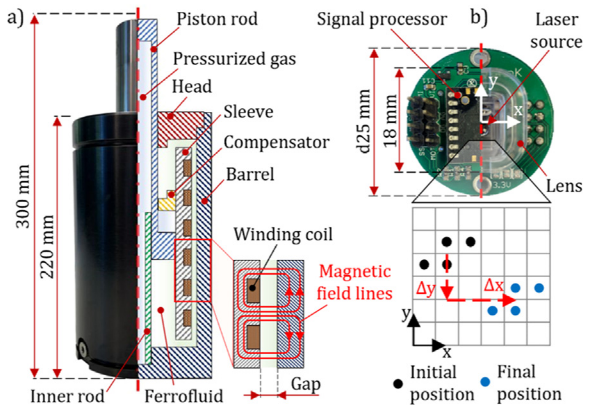

Fig. 1. (a) Ferrofluidic actuator, and (b) non-contact VCSEL sensor.

same time, it works as a volume compensator to balance the volume change during the piston stroke and allows for rapid return to the initial position. The stator winding incorporated into the sleeve generates a uniform magnetic field, which activates the ferrofluid along the 125 mm long cavity.

Fig. 2(a) shows the force versus stroke response obtained with different DC values. Unlike gas springs, the force response of the ferrofluidic actuator is constant and can be modulated over the working stroke according to the applied excitation current. The device presents a threshold force of about 8 kN due to the viscous behaviour of the ferrofluid flowing through the annular gap. Despite being a dissipative actuator, the response time has kept under 0.18 s, as fast as servo-valves commercially available and compatible with most mechanical forming processes, see Fig. 2(b). The main mechanical and electrical characteristics of the ferrofluidic actuator are given in Table 1, along with the physical characteristics of the ferrofluid. Details on the actuators design are in [15].

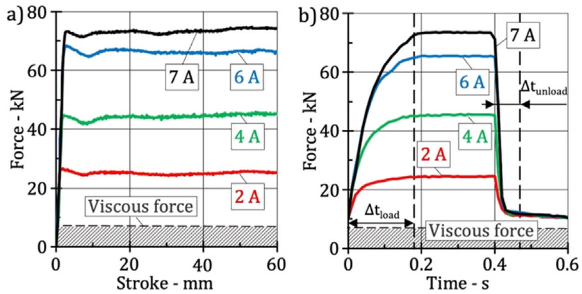

Fig. 2. (a) Force vs. stroke response, and (b) load and unload times of the ferrofluidic actuator as a function of DC.

Table 1
Ferrofluidic actuator specifications.

Parameter	Value
Nominal force	70 kN
Peak force	90 kN
Threshold force	8 kN
Stroke	75 mm
Outer diameter	120 mm
Copper wire diameter	0.8 mm
Current intensity range	0–7 A
Ferrofluid solid particle content	81%
Ferrofluid density	2.90 g/cm^3
Ferrofluid viscosity at 40 °C	0.21 Pa s
Operating temperature	−20 °C - 150 °C

3.2. Non-contact sensing

Real-time material flow measurements were performed using a Vertical Cavity Surface Emitting Laser optical (VCSEL) ADNS9800. The sensor consists of a laser source with a wavelength of 848 nm, a 30 × 30 8-bit pixel image acquisition system, and a digital signal processor for in-line data processing. To obtain the full resolution, the sensors were used at the maximum frame rate of 12,000 fps, with a working distance of 2.0 ± 0.1 mm from the metal sheet surface. Offline calibration over a velocity range from 0 to 15 mm/s resulted in an average resolution of 0.0035 mm. Fig. 1(b) shows the compact design of the sensors, which were embedded into the BH to measure the material flow measurement along the x and y directions of the sheet metal in the flange. Details of the equipment are in [16].

3.3. Control algorithm

Each actuator can be controlled in closed loop, either in *force* or *displacement* mode, as shown in the block diagram of Fig. 3. In both the cases, the objective parameters at the i th stroke increment can be optimized by means of analytical or numerical techniques.

With regards to the *force* mode, being the theoretical BHF at the i th stroke increment, $F_{i,ob}$, the corresponding pressure of the actuator,

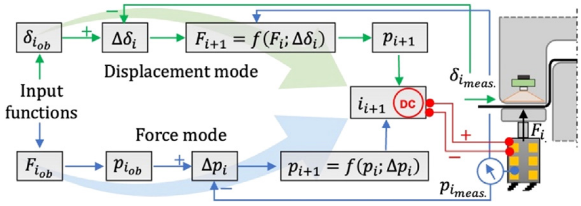

Fig. 3. Force and displacement control algorithms.

$p_{i,ob}$ is calculated and compared with the actual pressure $p_{i,meas}$, which is measured by a pressure transducer embedded in the barrel. The PID control provides in-line estimation of the error Dp_i and automatically varies the DC value at the (i + 1)-th stroke increment to meet the target force. Although relatively simple, the success of this approach depends on the correct estimation of the BHF and is not sensitive to metal flow variations.

In the *displacement* mode, the controlled parameter is the local material displacement in the flange, whose actual value $\delta_{i,meas}$ is compared with the target displacement $\delta_{i,ob}$ for a specific stroke increment. Thus, the input parameters of the PID are the displacements measured by the non-contact sensors, which allow for a local measurement of the metal flow at different points of the die. Then, the force of the actuators can be adjusted to increase or reduce the material draw in.

4. Validation

To validate the proposed system and approach, a laboratory-scale deep drawing operation of a hat-shaped profile was used as a reference. Despite its simplicity, the hat-shaped geometry allows for two independent flange zones, thus facilitating the application of different BHFs and evaluating their effects.

The experimental set-up is shown in Fig. 4 and was mounted on a servo-hydraulic dynamometer Instron-Wolpert, with a maximum compressive load of 1000 kN and a ram speed of 10 mm/s. The punch stroke was measured by a draw-wire sensor (model WPS-MK30 digital) having a measuring range of 500 mm and a linearity error equal to ±0.05% F.S.O. The active components of the equipment, including the punch, dies, and BHs, were manufactured in X153CrMoV12 (1.2379) steel, heat treated and polished to obtain a hardness of 54± 1 HRC and a Sa of 0.21±0.03 mm. The sheet used was mild steel DD11 (1.0332), with a nominal thickness of 0.8 mm and cut to 500 × 150 mm. Each BH embeds a VCSEL sensor described in Section 3.2, having the X- measurement direction aligned with the material flow in the flanges.

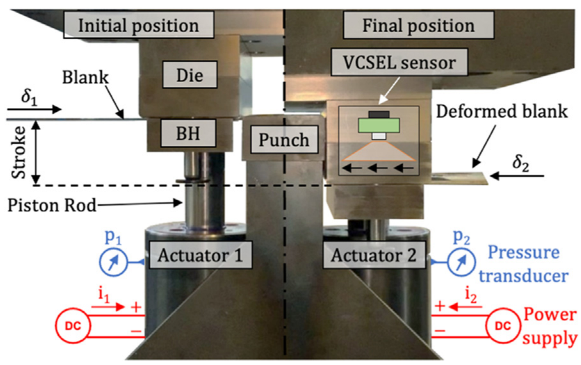

Fig. 4. The experimental setup for laboratory scale testing.

Two ferrofluidic actuators having a nominal force capacity of 70 kN were used to operate the BH. The devices were powered by a DC drive control unit capable of supplying a DC output in the range 0–12 A. Each actuator was equipped with a NAT 8252 TRAFAG pressure sensor (having a measurement range 0–400 bar with a linear accuracy of ±0.5% F.S.O.) to monitor its force during the test. Each actuator allowed for an independent control of the BHF applied to the two sides of the profile, thus making it possible to implement different blank holding strategies.

Three different validation tests were performed: firstly, the sensibility of the system was checked by deep drawing experiments in which the excitation current varied from 1 A to 7 A for only one actuator. Secondly, the possibility of alternating deep drawing and stretching conditions to reduce springback was tested. Lastly, the ability to maintain uniform drawing on both sides was tested by real-time control of material flow under different lubrication conditions. Table 2 summarizes the experimental plan, where the tests were labelled as *A*, *B* and *C* respectively. All the tests were conducted at a constant ram speed of 10 mm/s and with a repeatability of 3.

Table 2
Experimental plan.

	Actuator 1		Actuator 2	
Test	I (A)	Friction	I (A)	Friction
A	1	dry	1–7 (0.25 stepped)	dry
B	1; 3; 7 (r.[1]/c.[2])	dry	1; 3; 7 (r.[1]/c.[2])	dry
C	automatic	lubricated	automatic	dry

[1] Stepped.
[2] Constant.

5. Results

Fig. 5(a) reports the results of the deep drawing runs carried out to test the sensitivity of the system to different pressure values of the BH. For this purpose, while the force applied by actuator 1 was kept constant, the DC values for actuator 2 were varied in the range from 1 A to 7 A. A dry friction condition was used to avoid any difference in lubrication between the two sides. The results are plotted in terms of forces applied by the actuators, and flanges length difference at the end of the process, Δl = l_2-l_1. It is shown that material sliding was symmetrical for balanced applied DC values (Δl = 0), while the sheet under actuator 2 was stopped for values greater than 4.5 A, as indicated by a nearly constant value of Δl. Intermediate DC values (from 2 A up to 4.5 A) produced different material flow conditions on the two sides, thus making possible to control the flange lengths. Fig. 5 (b) shows the deep drawn profiles.

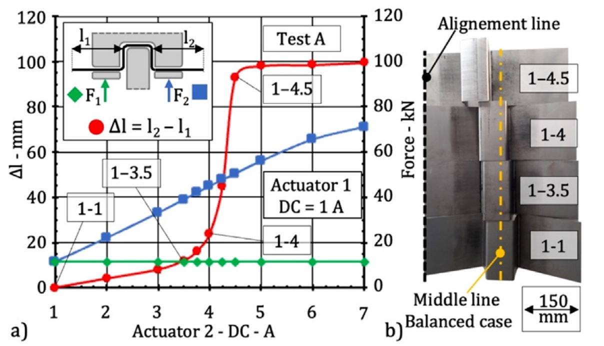

Fig. 5. (a) Different drawing in type A tests, and (b) stamped parts.

By varying the material flow in the flange during the process stroke, strains in metal sheet can be locally modified, thus affecting springback and the final shape of the profile, as represented in Fig. 6 for different BHF strategies. A hat-shaped profile obtained by applying a *constant* BHF was compared with one deep drawn by applying *stepped* BHF as shown in Fig. 6(a). The second strategy allowed for stretching conditions by increasing the BHF when needed to accurately form the corners (obtained at the beginning and the end of the ram stroke), while keeping it as low as possible in the middle of the stroke to minimize the risk of tearing. Numerical analyses carried out in LS-Dyna environment confirmed the different strains distribution with the two strategies, see Fig. 6(b), which resulted in a maximum

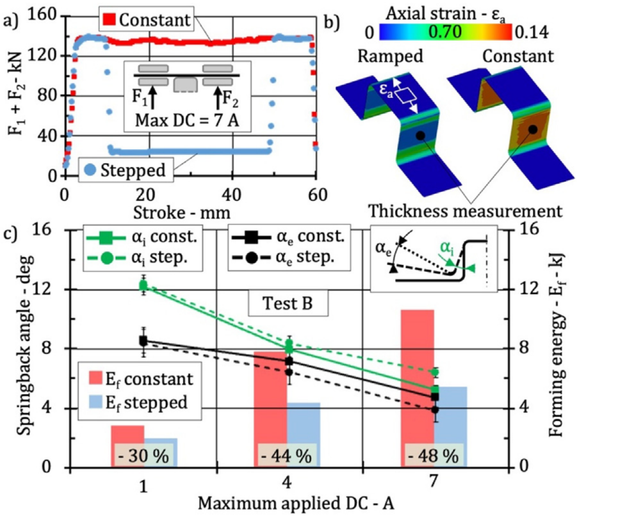

Fig. 6. (a) BHF in type B test, (b) strains computed by FE and, (c) springback measurements in tests with constant and stepped BHF.

experimentally measured thickness reduction of 0.11±0.02 mm and 0.03±0.01 mm, respectively, for constant and stepped BHFs. It was found that springback reductions of about 54% in the flange corner α_e and a 48% in the punch corner α_i – shown in Fig. 6(c) – were achievable using the stepped BHF strategy, with respect to the constant BHF at 1 A. Furthermore, by operating with stepped BHF the machine energy required to operate the BH has been reduced by 48% in the case of DC equal to 7 A, which represents an additional benefit for the energy balance of the entire process.

Finally, the possibility of fully adaptive adjustment of the BHF during deep drawing was tested. The case of different lubrication conditions on the two flanges was taken as a reference. The BH under actuator 2 was operated dry, while the one under actuator 1 was lubricated with Ratak Butex 171 produced by FUCHS®. The goal for the PID control, tuned on the process mathematical model, was to keep the same material flow (measured as sheet tangential displacement) under the flanges by varying the force applied by the actuators. Fig. 7 plots the difference in the measured material flow $\Delta\delta$ during the process, proving that the material sliding could be kept closed to the target value $\Delta\delta_{ob}$. The forces of the two actuators were adapted in real-time according to the control algorithm described in Section 3.2, increasing the applied force where the material was easier to flow due to the lubrication. Again, the final error was measured as the difference in length of the flanges at the end of the process and was equal to 0.35±0.22 mm.

6. Conclusions

The paper introduces a new mechatronic system for self-adaptive metal flow control in deep drawing. The system, which integrates a new family of ferrofluid-based actuators and non-contact laser optical sensors, enables accurate and flexible control of the BHF and can be easily integrated in already existing dies. The presented actuators allow for a working stroke of 70 mm, a peak force of 90 kN and response time lower than 0.18 s. The non-contact laser optical sensors guarantee a resolution of 0.0035 mm and have proven their worth even in oil-lubricated environments. The deep drawing of a hat-shaped profile was used as a reference case for validation purposes. It has been shown that the actuators have high force sensitivity in the DC range from 0 A to 7 A, and the BHF can be modulated from sliding to stretching conditions, thus affecting the accuracy and mechanical properties of the stamped parts. Finally, real-time

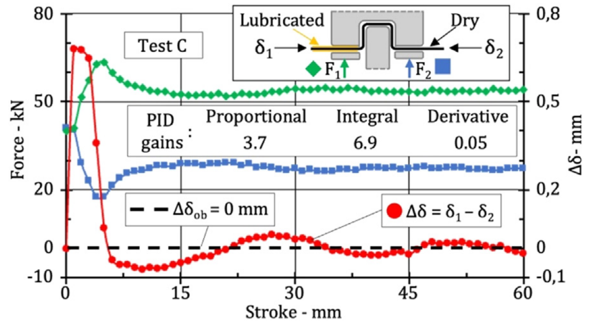

Fig. 7. Adaptive metal flow in the case of non-symmetrical conditions in the two flanges.

adaptive control was tested by reproducing non-uniform lubrication conditions on the two sides of the profile, with a maximum deviation from the imposed material flow of 0.35±0.22 mm, which is accurate enough for sheet metal stamping applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Yanagimoto J, Banabic D, Banu M, Madej L (2022) Simulation of Metal Forming – Visualization of Invisible Phenomena in the Digital Era. *CIRP Annals* 71(2):599–622.
[2] Allwood JM, Duncan SR, Cao J, Groche P, Hirt G, Kinsey B, Kuboki T, Liewald M, Sterzing A, Tekkaya AE (2016) Closed-Loop Control of Product Properties in Metal Forming. *CIRP Annals* 65(2):573–596.
[3] Doege E, Elend L-E (2001) Design and Application of Pliable Blank Holder Systems for the Optimization of Process Conditions in Sheet Metal Forming. *Journal of Materials Processing Technology* 111(1–3):182–187.
[4] Hassan MA, Takakura N, Yamaguchi K (2003) A Novel Technique of Friction Aided Deep Drawing Using a Blank-Holder Divided into Four Segments. *Journal of Materials Processing Technology* 139(1–3):408–413.
[5] Gavas M, Izciler M (2006) Design and Application of Blank Holder System with Spiral Spring in Deep Drawing of Square Cups. *Journal of Materials Processing Technology* 171(2):274–282.
[6] Gunnarsson L, Asnafi N, Schedin E (1998) In-Process Control of Blank Holder Force in Axi-Symmetric Deep Drawing with Degressive Gas Springs. *Journal of Materials Processing Technology* 73(1–3):89–96.
[7] Ghiotti A, Regazzo P, Bruschi S, Bariani PF (2010) Reduction of Vibrations in Blanking by MR Dampers. *CIRP Annals* 59(1):275–278.
[8] Li R, Bohn ML, Weinmann KJ, Chandra A (2000) A Study of the Optimization of Sheet Metal Drawing with Active Drawbeads. *Journal of Manufacturing Process* l:205–221.
[9] Bäume T., Zorn W., Drossel W.-G., Rupp G., 2016, Iterative Process Control and Sensor Evaluation for Deep Drawing Tools with Integrated Piezoelectric Actuators Manufacturing, 3, 3
[10] Bräunlich H., Neugebauer R., 2001, Closed Loop Control of Deep Drawing Processes, SheMet-International Conference on Sheet Metal, 529–538.
[11] Neugebauer R., Drossel W.-G., Mainda P., Roscher H.-J., Wolf K., Kroschk M., 2011, Sensitivity Analysis of Eddy Current Sensors Using Computational Simulation, Proceedings of the Symposium Progress in Electromagnetics Research, 450–454.
[12] Doege E, Seidel H-J, Griesbach B, Yun J-W (2002) Contactless On-line Measurement of Material Flow for Closed Loop Control of Deep Drawing. *Journal of Materials Processing Technology* 130:95–99. –131.
[13] Pat. App. 22155964.4, 2022, Actuation device.
[14] ISO 11901-1:2003 - Tools for Pressing - Gas Springs.
[15] Brun M, Ghiotti A, Bruschi S, Filippi S (2021) Active control of blankholder in sheet metal stamping. *Procedia CIRP* 100:151–156.
[16] Avago Technologies, Adsn-9800 LaserStreamTM Sensor, Datasheet.

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