

# Novel Approaches for In-line Draw-in Measurement Using Cost Effective Tactile Sensors

Lander Galdos<sup>1\*</sup>, Laura Muñiz<sup>1</sup>, Javier Trinidad<sup>1</sup>, Andoitz Aranburu<sup>2</sup>, Julian Ramirez de Okariz<sup>2</sup> and Aratz Barandiaran<sup>1</sup>

<sup>1</sup>Department of Mechanical and Industrial Production, Mondragon Unibertsitatea, Loramendi 4, Mondragon, Spain

<sup>2</sup>Fagor Arrasate S.Coop., San Andres Auzoa 20, Mondragon, Spain

**Abstract.** The application of Industry 4.0 and advanced controllers is advancing rapidly in deep drawing and stamping companies. The main goals of process monitoring, sensor data analysis, and the design of new controllers are process optimization and increased process robustness. These approaches directly result in reduced scrap and the development of more environmentally friendly processes. During process monitoring, measuring draw-in is crucial for both the try-out of new tools and production monitoring of stamping operations. This measurement allows for adjustments in lubrication and blank-holder forces, leading to a more robust process. This paper presents a novel method for the in-line draw-in measurement using cost-effective and robust tactile sensors based on pneumatic cylinders. The new sensor can track draw-in when curved blank-holders are used, allowing the monitoring of the full draw-in temporal curve. This paper first presents the design of the new sensor along with its accuracy measurements. Next, the sensor is tested using curved blank holders, and the buckling behaviour of the contacting finger is analysed. Finally, the sensor's performance in a real-world environment is evaluated.

**Keywords:** Stamping; Draw-in; Sensors; Industry 4.0

## 1 Introduction

Driven by emerging digital technologies, manufacturing ethos across the globe is transforming rapidly. From the automotive industry perspective, dies and press lines present themselves as critical but cost intensive hardware. Maximizing return on investment (ROI) against these assets is crucial for maintaining a healthy bottom line. Digital manufacturing tools and technologies could be leveraged in this context to monitor, analyse and control fully automated press lines and create more efficient and greener production processes.

To reach this scenario, the following developments are needed:

- In-tool embeddable actuators that can tune the material flow from the blank holder area towards the die cavity – also known as active shims in industry
- Cost-effective sensors to measure the draw-in during deep drawing
- New advanced intelligent hybrid controllers that can get the desired final shape of the outer contour or draw-in avoiding problems like wrinkling or splitting

Various solutions have been developed and implemented to measure the draw-in of stamped components and prevent defects such as tearing and wrinkling in deep drawing. These solutions include

linear displacement transducers [1], laser triangulation [2], roller balls, non-contact optical sensors [3], non-contact induction coils [4], eddy-current sensors [5], and arrays of piezoelectric sensors mounted under a protective layer near the tool surface [6].

While these technologies have demonstrated promising results in laboratory settings, they face challenges when integrated into real-world tools. Issues such as high levels of noise, vibrations, contamination, and mechanical collisions hinder their robustness in industrial applications.

Nevertheless, Fraunhofer IWU was among the first research centres to employ a laser triangulation sensor in collaboration with Volkswagen to monitor the stamping process of a large automotive component [7-10]. Similarly, Voestalpine Polynorm successfully applied this technology to monitor the draw-in of an aluminium hood. Building on these advancements, the Aspect European project later utilized six laser triangulation sensors and eight pyrometers to control the draw-in of the spare wheel well of the Opel Insignia [11-13]. The pyrometers accounted for friction variations caused by temperature increases during production, which also influence the draw-in of components.

These projects have demonstrated that monitoring draw-in using laser triangulation sensors positioned at strategic locations is a promising approach for industrial applications.

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\* Corresponding author: [lgaldos@mondragon.edu](mailto:lgaldos@mondragon.edu)

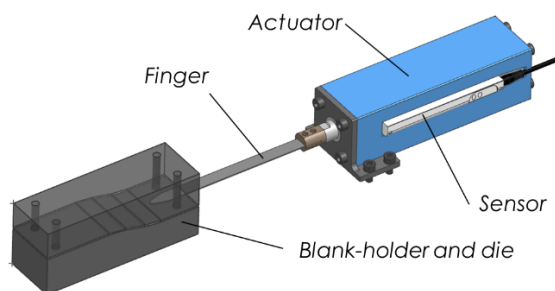
The work carried out by the authors in the I-Stamp European project, in collaboration with Ford Almussafes, highlighted several drawbacks of these sensors. The cost is quite high when multiple points of the component need to be monitored. More importantly, laser triangulation sensors cannot be used with curved blank-holders or thin sheets, lower than 0.6 mm, as the laser loses the tracking spot.

This paper presents a novel tactile draw-in monitoring sensor that is both highly cost-effective and suitable for use in curved dies. The innovative design incorporates a pneumatic cylinder that follows the sheet and a digital sensor that tracks the cylinder piston stroke, which directly corresponds to the actual draw-in of the sheet. The sensor is initially tested on a bench to evaluate its precision and analyse the buckling behaviour of the tactile finger. Finally, the results obtained from testing the sensor with a real stamping tool using three different materials are presented.

## 2 Novel tactile draw-in measuring sensor

The new tactile draw-in measuring sensor is shown in Fig. 1. It consists of a pneumatic actuator equipped with a digital sensor that monitors the piston stroke of the pneumatic cylinder. Additionally, it features an exchangeable finger made of spring steel, which is approximately one-tenth of a millimetre thinner than the sheet thickness. The finger can be easily replaced using two grub screws, allowing for adaptation to different sheet thicknesses and optimizing the cross-section to follow the sheet in non-flat blank-holders without buckling.

The pneumatic cylinder is equipped with flow control valves allowing for fine-tuned adjustment of the speed during sheet contact and cylinder recovery. Additionally, the pressure can be regulated to prevent finger buckling using pressure regulator.



**Fig. 1.** Design of new tactile draw-in monitoring sensor.

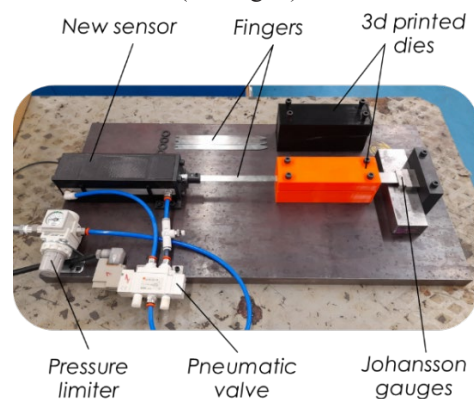
The working principle of the sensor is as follows. Initially, the cylinder is in its retracted position, waiting for a new precut to arrive at the tooling. At this stage, the finger maintains a gap of approximately 5 mm between its contact point and the precut. Once the tool closes and the precut is clamped between the die and the blank-holder, the press's virtual encoder activates the cylinder, advancing the finger until it makes contact with the precut before the punch interacts with it. During the deep drawing process, pressure is maintained to

ensure the finger follows the blank's contour, enabling precise draw-in measurement. Finally, after the press surpasses the bottom dead centre, the pressure is reversed, allowing the cylinder to return to its initial position.

## 3 Sensor testing at laboratory bench

### 3.1 Sensor calibration and repeatability study

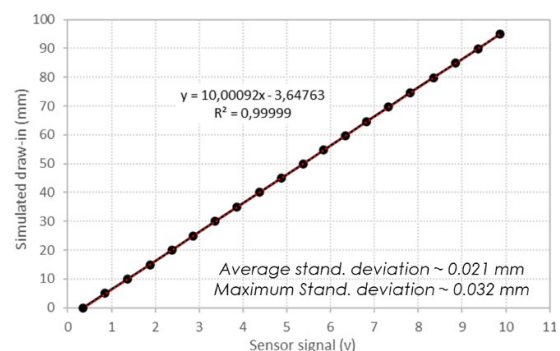
To calibrate the sensor assembly (cylinder + sensor + finger), considering the stiffness, repeatability, and cumulative errors of all components, a dedicated testing bench was designed and manufactured. The setup includes a base plate, the sensor with pneumatic accessories, and two different 3D-printed dies, one simulating a flat die and the other a severely curved die. Additionally, a stopper with Johansson gauges is used to test various draw-in values by incorporating gauges of different dimensions (see Fig. 2).



**Fig. 2.** Testing bench for laboratory testing of new sensor assembly.

Twenty different stroke values, in increments of 5 mm, were tested, with three repetitions per stroke. These tests facilitated the calibration and analysis of the sensor's repeatability. As shown in Fig. 3, the sensor exhibits excellent linearity, with an R-squared value close to 1.

Regarding repeatability, the average standard deviation across all 100 measurements was 0.021, while the maximum standard deviation for a single tested stroke was 0.032. These values are highly suitable for deep drawing applications and are difficult to achieve using a laser triangulation sensor or an artificial vision camera.



**Fig. 3.** Sensor calibration with standard deviation values.

### 3.2 Buckling behaviour of tactile finger

One of the weaknesses of the new sensor is the potential buckling of the finger when measuring large draw-in values. As the free length ( $l_0$ ) and friction between the finger and the tool (especially in curved cases) increase, the finger is more prone to buckling if its thickness and cross-section are too small.

According to Euler's equation for a fixed-fixed configuration, the critical buckling force of a beam can be determined by:

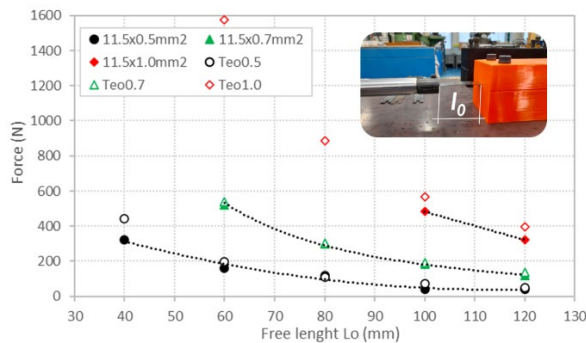
$$F_b = \frac{\pi^2 \cdot E \cdot I}{l_{bu}^2 \cdot \vartheta} \quad (1)$$

where  $F_b$  is the critical buckling force,  $E$  is the Young modulus of the beam or finger,  $I$  is the moment of inertia,  $l_{bu}$  is the free length of buckling and  $\vartheta$  is the safety factor. For the case of fixed-fixed configuration  $l_{bu} = l_0 \cdot 0.5$

To determine a safety factor for the new sensor assembly and aid in dimensioning the finger cross-section based on its thickness, three different fingers with cross-sections of 11.5x0.5 mm<sup>2</sup>, 11.5x0.7 mm<sup>2</sup> and 11.5x1.0 mm<sup>2</sup> were tested. The free length was varied from 40 to 120 mm in increments of 20 mm.

For each combination of free length and cross-section, the cylinder pressure was gradually increased until buckling was observed. The tests were repeated three times, and the critical buckling force was calculated based on the observed critical pressure. The experimentally determined critical buckling forces are represented in Fig. 4 as shaded points and dotted lines.

Using inverse calculation, the safety factor was adjusted to achieve a close match with the theoretical Euler equation. The best fit was obtained with a safety factor of 1.4, as shown in Fig. 4, demonstrating good agreement between theoretical predictions and experimental results.

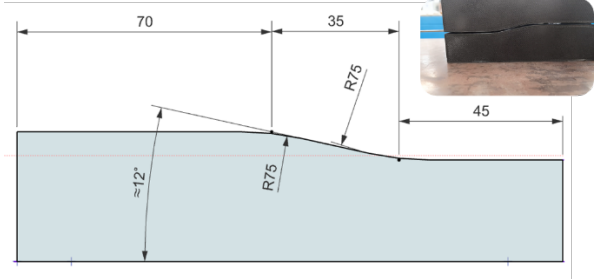


**Fig. 4.** Theoretical and experimental critical buckling forces for different finger cross section.

For a new tool where this solution is to be applied, the minimum force and free length of the finger can be determined through finite element simulation by modelling the finger's penetration. Using the buckling curve from Fig. 4, the finger design can be validated by ensuring that all force-stroke values remain below the critical buckling curve.

To validate the sensor's performance for curved blank-holders and dies, a highly contoured die was designed and manufactured using Fused filament fabrication (FFF) 3D printing (see Fig. 5). The sensor successfully navigated the curved die without any issues

of buckling, and the initial results were promising for applying this technology to complex tooling.



**Fig. 5.** 3D printed curved blank-holder to test buckling behaviour.

### 4 Sensor validation using a mechanical servo-press

After the validation of the new sensor at laboratory scale in a static test bench, real experiments were performed using a curved shape deep drawing tool. The tool and sensor were mounted in a Fagor servo-mechanical press of 4000 kN. The tool and sensor assembly are shown in Fig. 6.

The medium thickness (11.5x0.7 mm<sup>2</sup>) finger was used in the tests and three different material grades of 1.5 mm thickness were used, a DX54 mild steel, a DP780 dual phase steel and a AA5754 aluminium alloy.



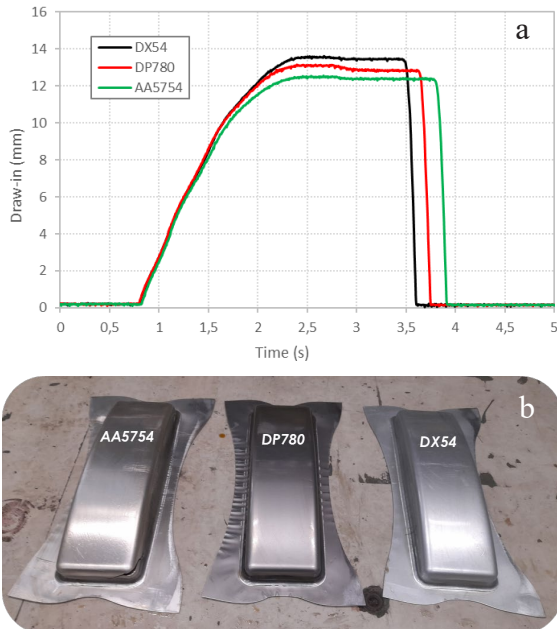
**Fig. 6.** New sensor assembly in a real deep drawing tooling.

The sensor was activated using the press's digital signals immediately after the blank-holder closed and was deactivated once the press reached the bottom dead centre.

Draw-in curves for the different tested materials are shown in Fig. 7a. As observed, for the same process parameters and press stroke, mild steel DX54 exhibited the largest draw-in value, followed by DP780 high-strength steel, and aluminium AA5754. The higher hardening of mild steel, combined with high anisotropy coefficients, forced the material to flow inward. In contrast, DP780 and AA5754 materials, with lower hardening and anisotropy values (especially the aluminium alloy), limited material flow, resulting in increased stretching of the material.

As shown in Fig. 7b, the aluminium part shows a split in the lower right corner, while the two steel components show no defects. This highlights the potential of the new sensor to detect process fluctuations

and identify poor working conditions. It is worth mentioning that the new sensor enables continuous monitoring of the draw-in signal, rather than just providing the final draw-in value as artificial vision cameras do. This capability was previously not possible with non-flat blank-holders and opens new possibilities for using advanced algorithms to detect process fluctuations, even when the final draw-in value remains the same.



**Fig. 7.** Experimental test results using the real tooling. a) Draw-in versus time curves for different materials and b) deep-drawn components using different materials.

## 5 Conclusions

A novel tactile draw-in monitoring sensor designed for use in curved dies, offering a cost-effective solution for continuous draw-in measurement during the deep drawing process was developed. The sensor incorporates a pneumatic actuator, a digital sensor, and an exchangeable finger made of spring steel, which follows the sheet contour to accurately measure the draw-in.

The new sensor system was calibrated and tested on a dedicated testing bench to evaluate its precision and repeatability, with results showing excellent linearity (R-squared value close to 1) and a low average standard deviation of 0.021 for 100 measurements.

To ensure the sensor's robustness and prevent buckling during large draw-in measurements, a series of tests were conducted on different finger cross-sections and free lengths. By utilizing the Euler equation and critical buckling force calculations, a safety factor of 1.4 was determined, which accurately predicted the sensor's performance and was validated through experimental results. These findings enable the design of the sensor's finger to be optimized for different applications, ensuring minimal buckling and maximum accuracy.

The sensor was able to detect differences in material behaviour, with mild steel DX54 showing the largest draw-in, followed by DP780 steel and aluminium AA5754 using a real deep drawing tool. The continuous

monitoring capability allows the sensor to identify process variations that may go unnoticed by traditional methods, even when the final draw-in value is the same. This opens new opportunities for applying advanced algorithms to detect process fluctuations and improve the quality control of deep drawing operations. Furthermore, the sensor's ability to measure draw-in in non-flat blank-holders, an area where traditional sensors struggle, provides a significant advantage in complex tooling applications.

The new sensor is currently being validated in real production tooling for a medium-sized automotive component. After fine-tuning the pneumatic pressure, the sensors have successfully completed multiple production runs without causing any interruptions.

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