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ORIGINAL ARTICLE

Experimental force monitoring and IIoT integration in the deep drawing process of gas cylinders

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Abstract

The deep drawing process is widely employed in the manufacturing of gas cylinders, where force monitoring plays a crucial role in ensuring process stability, product quality, and operational safety. However, the integration of experimental force monitoring systems with Industrial Internet of Things (IIoT) architectures in real industrial environments remains limited. This study presents the development and experimental validation of an IIoT-based force monitoring system applied to the deep drawing process of gas cylinders. The system employs load cells installed on an industrial press to acquire force signals in real time, combined with a low-cost data acquisition unit and wireless communication for data transmission and storage. Experimental tests were conducted on a 500-ton hydraulic press during the deep drawing of steel gas cylinders, allowing the analysis of force evolution throughout the forming cycle. The results demonstrate good signal stability and repeatability, as well as the capability of the proposed system to capture characteristic force patterns associated with the deep drawing process. The integration with an IIoT architecture enables real-time monitoring, data traceability, and remote access, supporting future implementations of process control and predictive analysis. The proposed approach demonstrates the feasibility of implementing experimental force monitoring aligned with Industry 4.0 concepts in industrial deep drawing operations.

Keywords Industry 4.0 · Industrial internet of thing (IIoT) · Stamping monitoring · Deep drawing

1 Introduction

In mechanical forming processes, particularly in sheet metal forming operations, the application of Industrial Internet of Things (IIoT) solutions enables significant improvements in terms of efficiency, traceability, and reliability of operational data. These capabilities support faster and more informed decision-making, contributing to process parameter optimization and the reduction of waste and failures associated with tool wear.

Advances in IIoT technologies allow sensors and actuators to be connected to the internet, enabling remote monitoring and control at any time and from any location. This technology facilitates communication between sensors and intelligent devices, improving equipment performance and increasing overall production efficiency. In this context, sensors can communicate with mobile devices and interact with each other, allowing the industry to adopt IoT-based solutions in several applications, particularly in the manufacturing sector. For instance, load cells can be used to measure

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and monitor forming forces during sheet metal stamping processes [1].

Cloud-based data transmission aims to integrate and efficiently share manufacturing resources, enabling the production of customized products with high efficiency. With the introduction of cloud manufacturing concepts, several topics have been widely investigated and discussed in both industrial and academic contexts. However, it is important to recognize that the transmission and management of manufacturing data in cloud environments still require further development and consolidation [2].

According to [3], the implementation of monitoring systems capable of providing information based on the most relevant stamping parameters and identifying process limits according to part geometry is of great importance for forming operations. Nevertheless, the integration of real-time experimental process monitoring aimed at predicting potential failures—based on the understanding of material behavior and the geometry of the forming tools—remains limited. This gap directly affects production costs and final product quality, highlighting the need for experimental monitoring solutions that can effectively support the sheet metal forming industry [4–11].

In this context, the development of a system capable of monitoring in real time the main parameters that directly influence the industrial stamping process within a production line can contribute significantly to the monitoring of key variables affecting sheet metal behavior during forming operations. Such a system makes it possible to minimize the main process-related defects and to demonstrate the direct influence of tool geometry on the final shape of the formed component [12–20].

To develop a device capable of performing real-time process monitoring, it is necessary to employ a system that transmits the information collected during manufacturing to a remote-access platform. Additionally, the monitoring device must be installed on or integrated into the forming tool in order to collect data more accurately in the plastically deformed region. The development of sensors capable of acquiring relevant information to continuously optimize and improve manufacturing processes is therefore expected, although such solutions have not yet been widely implemented on industrial shop floors [21–32.

The present article adopts an integrated approach to enhance the efficiency and quality of stamping processes in the mechanical industry. The main novelty lies in the specific application of the Industrial Internet of Things (IIoT) to collect real-time force data throughout the entire stamping cycle. The proposed remote monitoring system enables operators to track the forming process in real time from any location, further reinforcing the originality and industrial relevance of the research.

This work combines two research fronts of recognized academic and industrial importance. The first concerns mechanical forming processes, particularly deep drawing, applied to the manufacturing of components with high structural responsibility, such as gas cylinders. The second is associated with the incorporation of Industry 4.0 and Industrial Internet of Things (IIoT) concepts into the manufacturing environment through press instrumentation, real-time data acquisition, and integration with cloud-based digital platforms.

2 Materials and methods

2.1 Press used in the stamping process

The mechanical press used in this study is an ERFURT eccentric press, a piece of equipment widely employed in industry, particularly in the stamping of gas cylinders, which requires the application of high forming forces. With a nominal capacity of 500 tons, the press is designed to provide robustness and structural rigidity, ensuring stable operation even under high-load conditions. In addition, the press requires low maintenance, contributing to high operational availability and reliability. Its high productivity rate makes it particularly suitable for large-scale production processes.

Among its main technical characteristics, the press features a precise control system that allows accurate adjustment of operating parameters, such as forming force and stamping speed, as well as a robust construction capable of withstanding intensive working cycles. The press is also equipped with safety systems designed to protect the operator and prevent operational failures. Fig. 1 illustrates the ERFURT 500-ton eccentric press used in this study.

Furthermore, the press design allows easy integration with industrial automation and remote monitoring systems, which further optimizes the production process and facilitates predictive maintenance strategies.

The stamping die set installed on the press is illustrated in Fig. 2 and is used for manufacturing the product through an industrial stamping process. The tooling was specifically designed to meet the requirements of the process and the geometry of the final product. Its manufacturing involved several advanced processes, including computer numerical control (CNC) machining, wire electrical discharge machining (EDM), grinding, and heat and surface treatments, ensuring high dimensional accuracy, wear resistance, and structural integrity during operation.

The tool geometry, which includes a complex bending profile, was selected due to its ability to form components with high complexity and precision. This geometric characteristic is particularly relevant to the present study, as it

Fig. 1 ERFURT 500-ton eccentric press

enables a detailed analysis of forming conditions such as force distribution, material deformation, and potential process failures. In addition, the chosen geometry allows the evaluation of critical factors such as thermal distribution and the mechanical behavior of the material during stamping.

The tooling was manufactured using high-durability materials, specifically AISI D2 tool steel, combined with heat treatment, surface treatment, and tempering, in order to withstand the demanding conditions of high-volume stamping processes. The surface finish quality of the tool was carefully controlled to minimize friction during forming and to ensure extended tool life.

This stamping tool was selected for analysis due to its ability to provide an efficient and repeatable forming cycle, enabling the production of components with the quality required for industrial applications. Fig. 2 illustrates the detailed model of the tooling used in the study.

To provide better contextualization, relevant information regarding the tooling and the press is summarized in Table 1. This table presents specifications such as die material, punch material, press operating speed, and maximum press force. These parameters are essential for a comprehensive understanding of the performance of the press and tooling during the forming process.

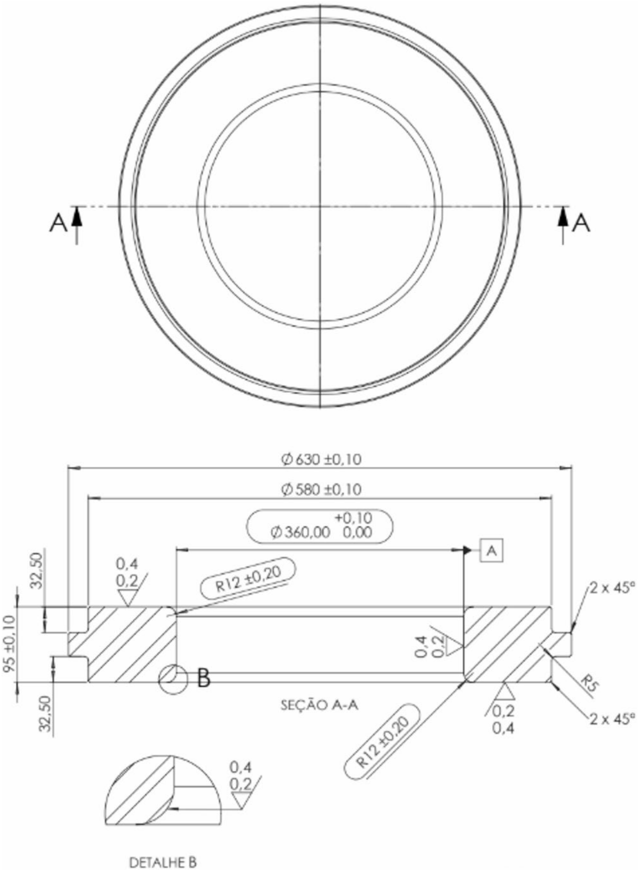


Fig. 2 Lower die of the deep drawing tooling

Table 1 Specifications of the tooling used in the studied Stamping process.Source: author (2025)

Description	Specification
Press	Hydraulic
Maximum nominal force	500 T
Die material	AISI D2
Punch–die clearance f	2,650 mm
Sheet thickness	2,650 mm
Punch material	D2 steel with PVD coating
Press speed v	25 à 35 gpm

These specifications help contextualize the scale of the application and the technical details of the tooling, enabling a more accurate analysis of the system. They are also crucial for evaluating process efficiency, thermal behavior during operation, tool durability, and key variables that must be controlled to optimize production. With this information, it becomes possible to identify potential areas for improvement and to implement adjustments aimed at enhancing both product quality and productivity .

For product manufacturing, SAE 1008 GL1 steel supplied by USIMINAS was used. The maximum chemical composition includes 0.08% carbon, 0.4% manganese, 0.011% phosphorus, and 0.08% sulfur. This steel grade is widely used in industry due to its good formability, weldability, and mechanical strength, making it suitable for stamping processes.

The selection of SAE 1008 steel was motivated by its excellent response during stamping, providing improved plastic deformation, reduced risk of cracking, and fewer forming defects. In addition, the material exhibits good structural uniformity and controlled friction behavior, which are essential characteristics for ensuring final product quality and tooling durability.

Another important factor is its favorable cost–benefit ratio, as SAE 1008 offers a balance between mechanical properties and ease of processing, improving overall process efficiency. This steel is commonly used in gas cylinder manufacturing, as illustrated in Fig. 3, which requires high formability and dimensional accuracy.

Within this context, the system developed in this work represents an intermediate solution between conventional sensors and fully integrated intelligent systems, enabling the acquisition of the real stamping force behavior in an industrial environment, with low cost and minimal interference in the production process.

In the industrial facility where the experiments were conducted, a FLIR ZLV-FLIRE49001 thermographic camera was used, as shown in Fig. 4, to perform temperature measurements of the sheet during the forming process. The main objective was to analyze the thermal behavior of the material, monitor temperature variations throughout the stamping process, and evaluate possible microstructural changes.

The monitoring system was used to record thermal variations during the process. This approach enables more precise control of stamping operations, identification of critical heating zones, and process adjustments aimed at reducing defects and improving production efficiency.

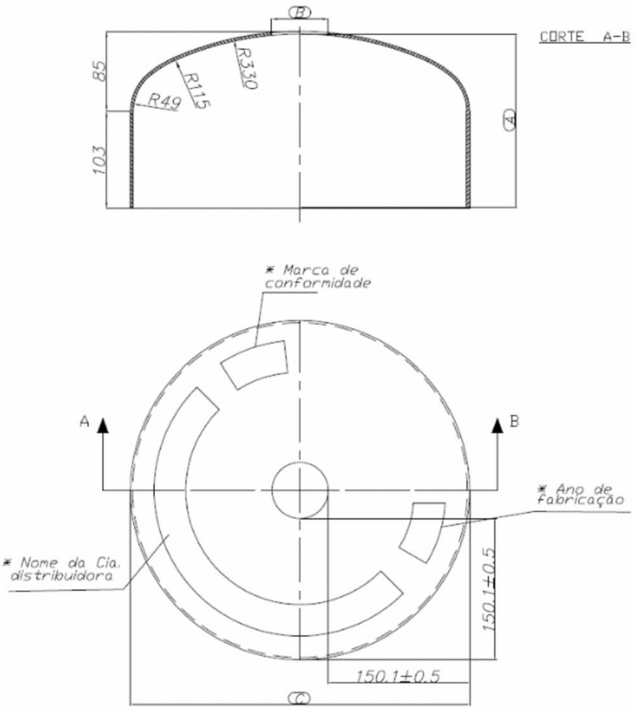


Fig. 3 Stamped gas cylinder product

Fig. 4 FLIR ZLV-FLIRE49001 thermographic camera

2.2 Data acquisition system

The data acquisition board selected for the process is the ESP32-C3, chosen due to its high processing capability, low power consumption, wireless connectivity (Wi-Fi and Bluetooth), and ability to support multiple sensors simultaneously. To ensure proper integration with other devices, it is essential to verify the available analog and digital ports, ensuring accurate and efficient connections while avoiding interference and guaranteeing data fidelity [33–41].

The ESP32 also enables real-time data transmission using the MQTT protocol, as well as Wi-Fi and Bluetooth communication, allowing integration with remote monitoring systems and data storage on local servers or cloud platforms. A graphical user interface was employed to facilitate data visualization and processing. This approach makes the system more dynamic, allowing rapid process adjustments and contributing to continuous improvement of stamping quality [42–51].

2.3 Instruments used for device assembly

As a preliminary step in the development of the data acquisition system, an attempt was made to identify the output signal associated with the stamping force through the RS485 communication interface available on the press, as illustrated in Fig. 5. This analysis aimed to verify the existence of an active signal on the bus that could be used for direct process data acquisition, potentially reducing the need for additional instrumentation.

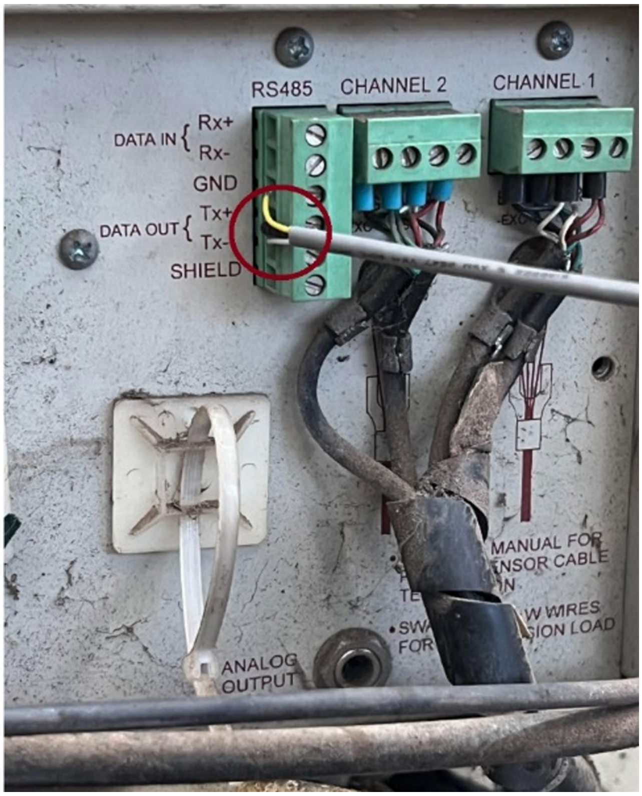


Fig. 5 RS485 communication interface

Fig. 6 RS485 connection to the oscilloscope

The RS485 interface was directly connected to a digital oscilloscope, as shown in Fig. 6, allowing observation of the electrical behavior of the bus during press operation. The oscilloscope was used to monitor voltage variations, the presence of differential signals characteristic of the RS485 standard, and any data transmissions synchronized with the stamping cycle.

During the tests, no electrical signals compatible with active communication were detected on the RS485 bus, even with the press in operation. Oscilloscope analysis indicated an absence of significant activity on the differential lines, suggesting that the interface was either not enabled for data transmission, did not provide stamping force information, or operated under proprietary configurations inaccessible under the evaluated conditions.

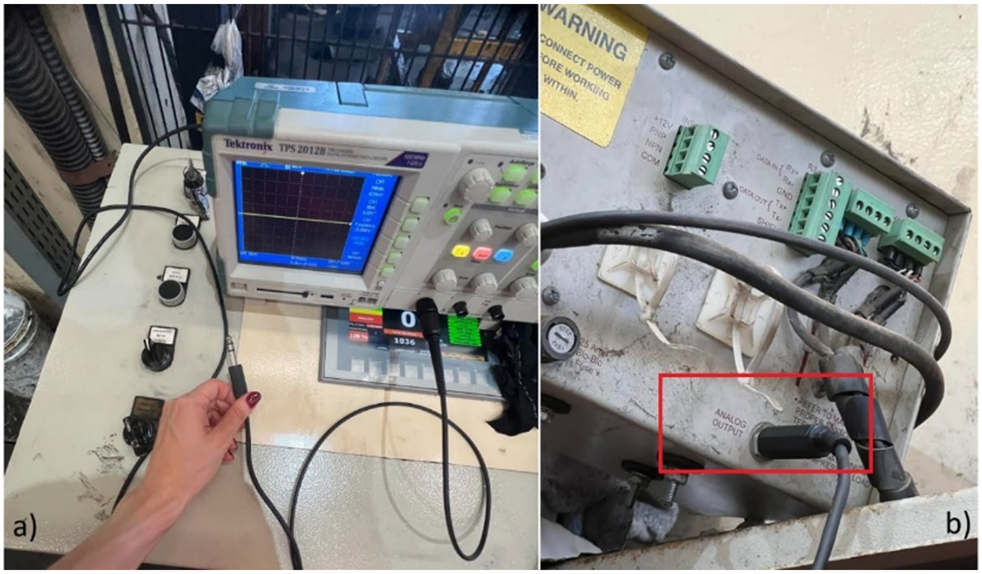
Subsequently, an alternative approach was investigated to continue the development of the data acquisition system and the implementation of the monitoring device firmware. An experimental verification of the analog output of the load cells installed on the press was performed using a digital oscilloscope. This step aimed to evaluate the electrical behavior of the signal generated by the load cells during stamping and to ensure compatibility with the input range of the analog-to-digital converter (ADC) of the microcontroller used in the device, as shown in Fig. 7.

The load cells provide a low-amplitude differential signal, typically in the millivolt range, proportional to the applied force during the stamping cycle. Therefore, direct measurement of this signal was essential for defining the gain parameters of the instrumentation amplifier and for determining the relationship between electrical voltage and mechanical force, later implemented in the embedded system programming.

The oscilloscope was connected to the output terminals of the load cell, enabling real-time observation of the analog signal during press operation. This instrumentation made it possible to identify maximum and minimum signal amplitudes, signal stability over time, the presence of electrical noise, and potential distortions associated with the industrial environment. In addition, time-domain analysis allowed visualization of the force profile throughout the stamping cycle, highlighting the load application moment and the dynamic behavior of the process.

Based on oscilloscope measurements, it was verified that the voltage range generated by the load cells was within the operational limits expected for the conditioning system and the microcontroller ADC. These data were essential for defining acquisition parameters such as ADC resolution, sampling rate, and saturation limits, as well as for implementing the voltage-to-force conversion routine, expressed in tons, in the device firmware.

Fig. 7 (**a**) Analog cable connection to the oscilloscope; (**b**) verification of the analog output signal of the load cells



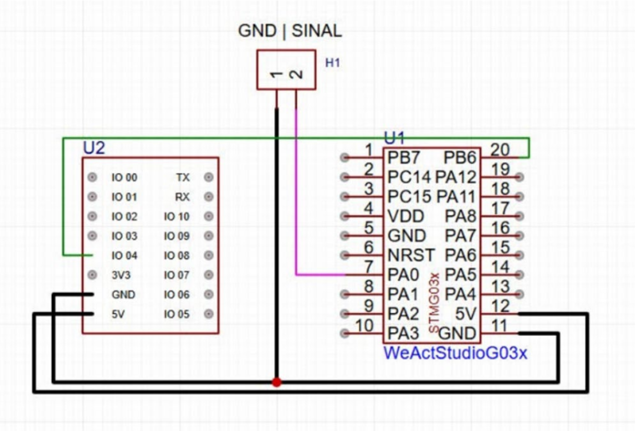


Fig. 8 Electrical circuit diagram for the ESP32-C3 and STM32G030 microcontroller

Thus, the use of the oscilloscope represented an indispensable step in the development of the monitoring system, ensuring that the analog signal from the load cells was properly understood, conditioned, and digitized. This prior verification contributed to the reliability of the measurements performed by the developed device, ensuring that the force values obtained during the gas cylinder stamping process accurately represented the real behavior of the press and were suitable for the experimental analysis proposed in this work.

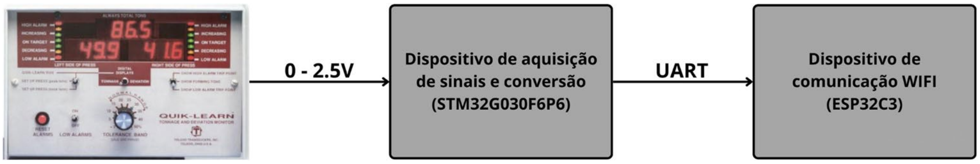
To assemble the data acquisition board, a printed circuit board, wiring, the ESP32-C3 acquisition board, an STM32G030 microcontroller as illustrated in the electrical diagram in Fig. 8, and a 5 V DC power supply were used. Connections were established between the load cells and the acquisition device, and the ESP32-C3 was connected to the Arduino IDE for system parameterization. To collect stamping forces during gas cylinder production, a data acquisition system was developed consisting of an STM32G030 microcontroller, responsible for signal sampling and preprocessing, and an ESP32-C3 module, responsible for Wi-Fi transmission for cloud storage.

The load cell operates in a Wheatstone bridge configuration and is powered by a stabilized excitation reference. The low-amplitude differential output signal is amplified by a low-noise instrumentation amplifier with gain adjusted to utilize the full range of the 12-bit ADC of the STM32. A second-order analog anti-aliasing filter is applied prior to A/D conversion, as illustrated in Fig. 9.

Sampling was configured per channel, triggered by a dedicated timer and collected via DMA to ensure CPU efficiency. After conversion, digital filtering (moving average/FIR), two-point calibration, and extraction of relevant parameters (force peak, peak time, integrated energy) were performed. The data were then packaged and transmitted to the ESP32 via UART using a binary protocol with CRC verification. The data were subsequently transmitted to a cloud-hosted Excel spreadsheet for later analysis, as shown in Fig. 10.

Data from the load cells installed on the press were locally acquired and processed by the STM32G030

Fig. 9 Signal acquisition and conversion system



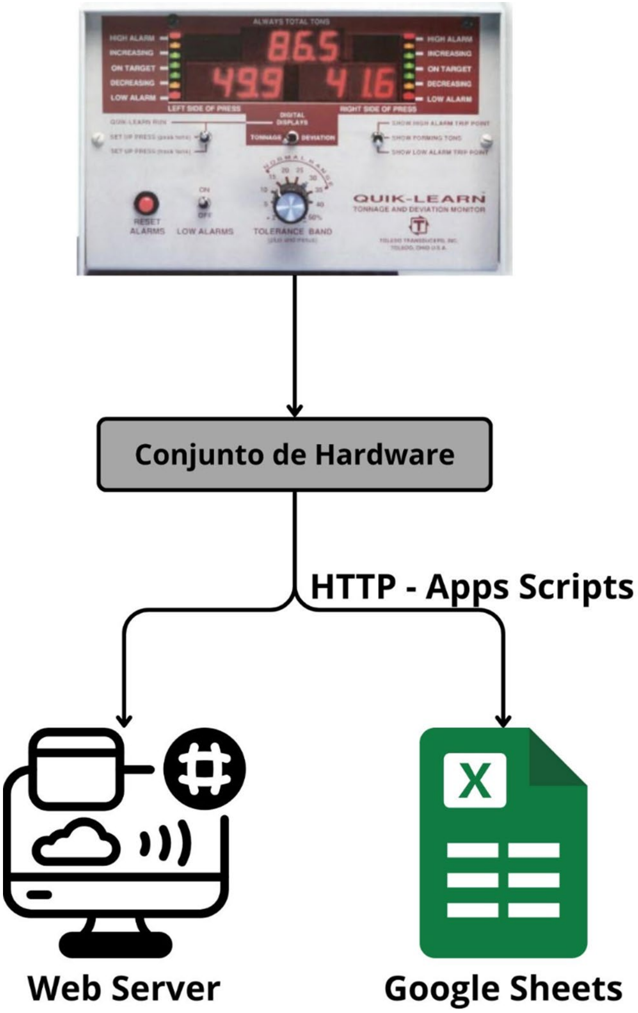


Fig. 10 Cloud-based data transmission model

microcontroller, ensuring deterministic behavior and independence from network connectivity. Subsequently, the data were transmitted via the ESP32-C3 module to public cloud storage using a Software as a Service (SaaS) solution. Fig. 11 shows the fully assembled monitoring device integrating all components.

The adoption of a free public cloud solution was a methodological decision aligned with the experimental scope of this work. Considering data volume, sampling rate, and research objectives, the resources offered by free platforms were sufficient for data storage, organization, and analysis without compromising measurement integrity or reliability.

It should be noted that the proposed architecture is independent of the cloud service provider, since the critical acquisition, conditioning, and initial signal processing layers are performed locally. Therefore, replacing the platform with paid or private solutions can be achieved without changes to the instrumentation or firmware, demonstrating the scalability and industrial applicability of the approach.

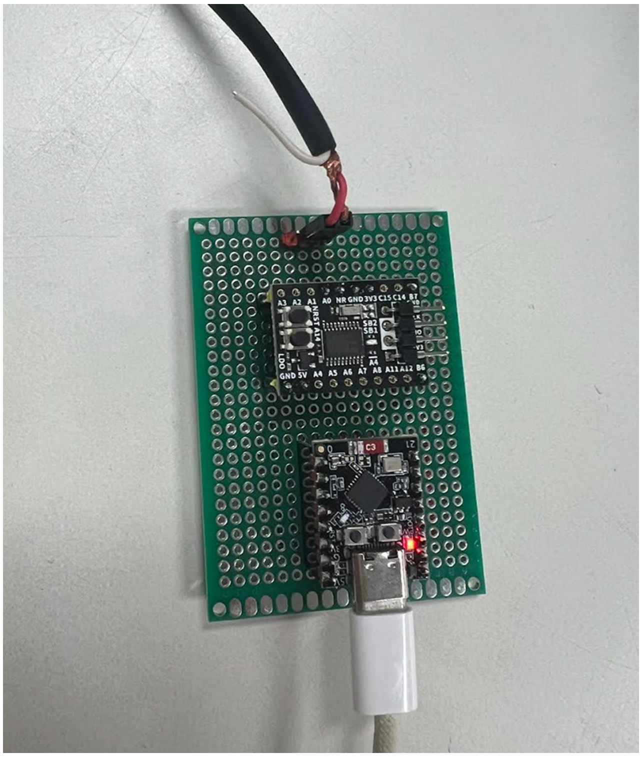


Fig. 11 Device for industrial stamping force monitoring

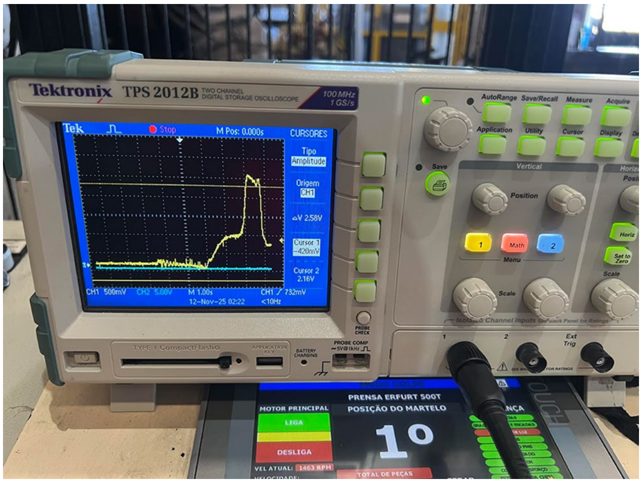


Fig. 12 Analog signal at the load cell output

2.4 Analysis of the analog signal from the load cells

The Fig. 12 presents the analog signal obtained directly from the output of the load cells installed on the press during a stamping cycle, measured using a digital oscilloscope. This experimental step aimed to characterize the electrical behavior of the signal associated with mechanical load application and to verify its suitability for subsequent acquisition and processing by the embedded system developed in this study.

Initially, a low-amplitude region with small fluctuations is observed, corresponding to the idle state of the press, in which no significant force is applied to the tooling. Subsequently, a progressively increasing voltage ramp is observed, associated with the onset of contact between the punch and the sheet and the gradual increase in force during the deep drawing process. This behavior demonstrates the sensitivity of the load cells to variations in applied mechanical load.

The signal reaches a well-defined maximum value, characterizing the voltage peak corresponding to the moment of maximum mechanical loading during the stamping cycle. This peak is directly related to the maximum effort imposed on the material during the formation of the gas cylinder dome. After this point, a sharp voltage reduction is observed, indicating load release and the end of the forming cycle.

The measured signal amplitude is on the order of volts, compatible with the input range of the ADC of the microcontroller used in the acquisition device. No signal saturation was observed, confirming the adequacy of the adopted signal conditioning and the correct definition of system gain. The presence of low-amplitude electrical noise is consistent with the industrial environment and was addressed in subsequent digital filtering stages implemented in the firmware.

Thus, experimental analysis of the analog signal confirms that the load cell output exhibits behavior consistent with the physical phenomenon of the stamping process and is suitable for digital acquisition and subsequent conversion into force values. These results supported the implementation of the acquisition and processing routines in the embedded system, ensuring that the load data obtained during gas cylinder stamping are representative and reliable for the experimental analysis proposed in this work.

2.5 Instrumentation and data acquisition system architecture

The experimental system architecture consists of three main layers: local signal acquisition, embedded processing, and data storage. The load cell is configured as a Wheatstone bridge and excited by a stabilized voltage source. The low-amplitude differential output signal is amplified by a low-noise instrumentation amplifier with gain adjusted to properly utilize the dynamic range of the 12-bit ADC of the STM32G030 microcontroller. A second-order low-pass analog filter is applied prior to A/D conversion, acting as an anti-aliasing filter.

Signal sampling is performed periodically, triggered by an internal microcontroller timer, ensuring deterministic behavior and measurement repeatability. The acquired data undergo digital filtering and calibration, enabling conversion into force values expressed in physical units.

After local processing, the force peak data from each stamping cycle are transmitted via UART to the ESP32-C3 module, responsible for wireless communication with the Wi-Fi network. Data storage is performed in a public cloud-hosted spreadsheet, allowing data organization and subsequent analysis of the time series obtained during experimental trials.

2.6 Experimental procedure and system calibration

The development of the stamping force monitoring system began with experimental verification of the analog output available on the stamping machine, a fundamental step for defining the signal acquisition and processing strategy. This verification aimed to identify voltage range, temporal behavior, and noise presence, ensuring compatibility with the proposed electronic system.

For this purpose, the machine's analog output was monitored using an oscilloscope, allowing direct visualization of the signal during real gas cylinder stamping cycles. Signal analysis enabled identification of maximum and minimum voltage amplitudes and their variation throughout the forming cycle. These data served as the basis for signal conditioning design, instrumentation amplifier gain definition, and selection of the operational range of the microcontroller ADC.

Based on oscilloscope characterization, the relationship between electrical voltage and applied force was established and subsequently implemented in the microcontroller programming to calculate force values expressed in tons. This step ensured coherent and physically meaningful conversion of measured voltages into load values.

After preliminary signal verification, system calibration was performed using certified weights applied at multiple points across the load cell operating range. From these tests, a linear relationship between measured output voltage and applied force was determined, enabling direct conversion of digital readings into load values during stamping experiments.

Experimental trials were conducted on a press used for gas cylinder forming, with the load cell positioned to record applied force during each stamping cycle. During operation, the system automatically identified the force peak of each cycle, which was adopted as the representative process parameter.

The sampling rate was defined based on prior oscilloscope analysis, ensuring adequate temporal resolution to capture force evolution during stamping without compromising system stability or data reliability.

2.7 Storage and organization of experimental data

Experimental data processed locally by the microcontroller were transmitted via Wi-Fi to a public cloud environment using a Software as a Service (SaaS) solution. This choice was motivated by ease of access, low cost, and suitability for the volume of data generated in the conducted trials.

Analysis of the collected data indicates that the measured press force exhibited predominantly stable behavior throughout the experiment, with values mostly concentrated in the approximate range of 255–265 tons. During most of the interval between 15:06 and 16:02, measurements fluctuated slightly around a mean value, indicating process regularity and good repeatability of the measurement system. Small fluctuations are expected in real stamping operations and may be associated with natural material variability, friction between tool and workpiece, minor positioning differences, or dynamic response of the acquisition system.

Notably, isolated force peaks were observed, such as values close to 267.9 tons, as well as more pronounced drops, particularly the final measurement around 219.5 tons, which deviates from the previously observed pattern. These deviations may indicate transient events such as cycle start or end, load release, signal interference, or momentary changes in press operating conditions. Within the scope of this study, these results reinforce the importance of time-domain force signal analysis, enabling identification of steady-state regions and potential anomalies, as well as supporting validation of the instrumentation system and correlation between applied force and material behavior during stamping.

Preliminary statistical analysis of the data supports the interpretation of a stable press operating regime during most of the operation, as force value dispersion around the mean is relatively low when extreme points are excluded. This behavior indicates that the press drive and control system, as well as the tool–material assembly, maintained consistent operating conditions throughout the analyzed cycle. Such stability is essential to ensure stamping process repeatability, reduce dimensional variability of produced parts, and enhance the reliability of experimental results obtained in this research.

In addition, identification of isolated variations and outlier values provides important insights for evaluating data acquisition system quality and understanding the physical phenomena involved in the process. These deviations may be related to electrical noise, sampling delays, mechanical vibrations, or abrupt changes in press loading state. Therefore, detailed time-domain force signal analysis not only characterizes the mechanical behavior of the stamping process but also validates the adopted experimental methodology, reinforcing the robustness of the results presented.

The use of cloud storage in this work is exclusively intended for data storage, organization, and traceability. No evaluation of cloud computing platform performance, security, or scalability was conducted. It is emphasized that the critical layers of signal acquisition, conditioning, and initial processing are performed locally, ensuring independence from network connectivity for obtaining measurements.

Experimental analysis was conducted based on real-time monitoring of press force through a web-based interface accessible via browser at IP address 172.20.10.4, as shown in Fig. 13. This interface displays the graph labeled “TON Monitor,” allowing continuous observation of force behavior during press operation. The acquisition system enables dynamic data visualization, facilitating identification of variations over time and providing an effective tool for stamping process analysis.

From the graph, force values are observed to remain mostly concentrated around the 255–265 ton range, with small oscillations throughout the monitored interval. This characteristic indicates that the process operates predominantly in a stable regime, without abrupt variations or significant erratic behavior. The observed stability is a positive indicator of both press mechanical performance and the reliability of the adopted measurement system.

The use of a real-time visualization system also enables analysis of process dynamics, highlighting natural oscillations resulting from press operation cycles, tool–material contact, and intrinsic forming characteristics. Such variations are expected in real industrial processes and reflect the interaction between mechanical parameters, friction conditions, and structural response of the equipment.

Another relevant aspect of experimental analysis is the ability to identify transient events, such as small force peaks or drops visible along the curve. These events may be associated with momentary variations in part positioning, material heterogeneity, or fluctuations in the drive system. Detection of such phenomena in real time is essential for studies aimed at improving process control and preventing operational failures.

Thus, the experimental methodology adopted, based on continuous force monitoring through a web interface, proved adequate for characterizing press behavior during stamping. The obtained dataset provides a solid basis for subsequent analyses, enabling both validation of the instrumentation system and correlation of experimental results with real process behavior discussed throughout this work.

2.8 Considerations on the experimental scope

It is important to emphasize that the system developed in this work was designed with a restricted focus on measuring stamping force during gas cylinder production, serving as

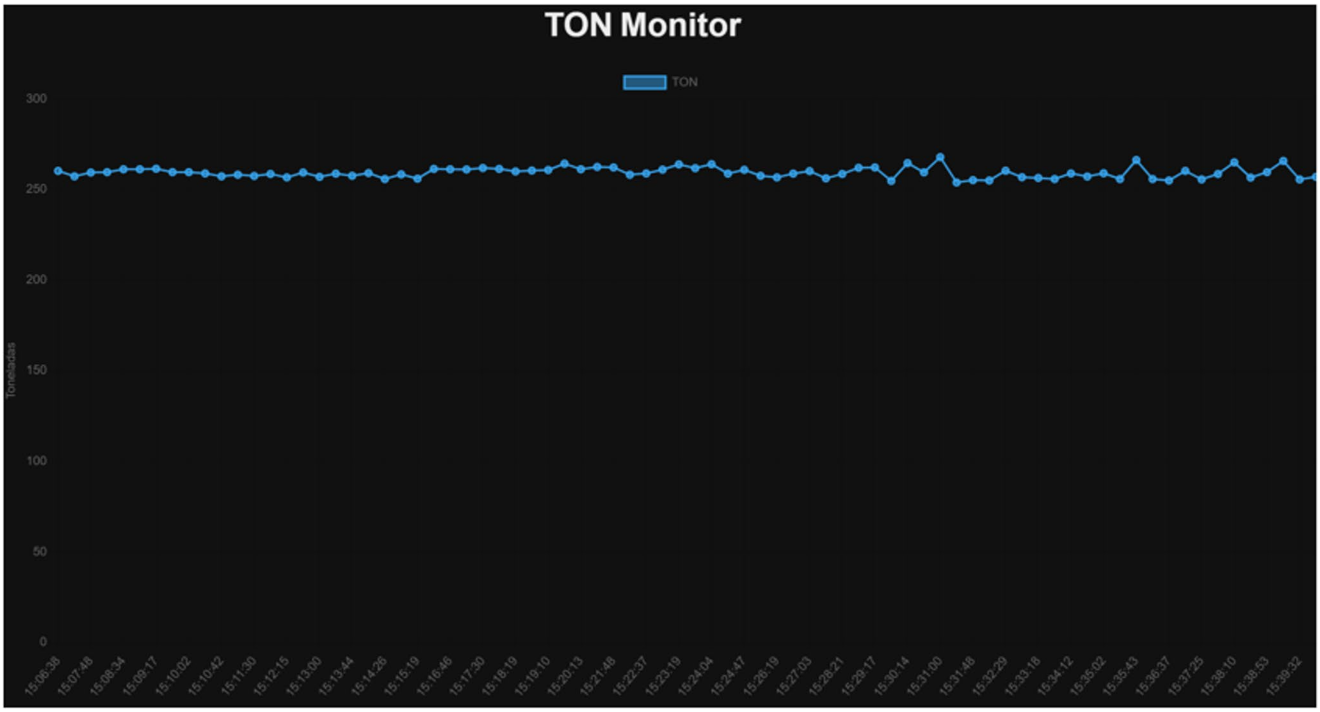


Fig. 13 Real-time monitoring of stamping force

an experimental foundation for mechanical forming process analysis. Aspects such as vibration analysis, energy consumption, advanced graphical interfaces, or machine learning applications are beyond the experimental scope of this research and are therefore not addressed in the presented results.

Nevertheless, the proposed architecture demonstrates potential for future expansion to include additional variables and functionalities, although such extensions are not experimentally validated within the scope of the present study.

3 Results and discussions

3.1 Validation of the force monitoring device

The validation of the proposed device was carried out based on the acquisition of the analog signal obtained from the press instrumentation system, previously verified using a digital oscilloscope. This step made it possible to confirm the stability, linearity, and variation range of the voltage signal generated as a function of the applied force during the stamping process. The measured voltage values were subsequently incorporated into the microcontroller firmware, enabling the conversion of the electrical signal into force values expressed in tons.

The experimental tests demonstrated that the device exhibits stable behavior throughout the press operating cycles, with no significant noise or signal loss that could compromise measurement reliability. The repeatability of the readings over multiple cycles indicates that the developed system is suitable for industrial real-time monitoring applications.

3.2 Analysis of force curves during the stamping process

Based on the validated device, force–time curves were obtained for different stages of the deep drawing process. The curves reveal a progressive increase in the applied force as the sheet metal comes into contact with the tooling, reaching a peak associated with the phase of greatest plastic deformation and sheet–tool friction. Subsequently, stabilization and a reduction in force are observed at the end of the cycle.

The maximum force values recorded are consistent with the nominal capacity of the 500-ton press and with data reported in the literature for similar forming processes. The analysis of the curves allows the identification of repeatability patterns between cycles, evidencing process stability and the potential application of the system for detecting operational deviations, such as tool wear or material variability.

The results obtained from the force measurements indicate that the stamping process operated predominantly under a quasi-steady regime, with force values concentrated within a relatively narrow range for most of the test duration.

This concentration around a mean value suggests consistent mechanical behavior of the press during operation, reflecting good interaction between the processed material, tooling, and operational parameters. Such behavior is essential to ensure process repeatability and to obtain products with controlled dimensional and structural quality.

The temporal analysis of the force signal reveals small oscillations throughout the cycle, which are inherent to mechanical forming processes and may be attributed to factors such as local friction variations, material heterogeneities, and dynamic responses of the press drive system. Despite these fluctuations, no continuous increasing or decreasing trend in force was observed, indicating the absence of progressive instabilities such as excessive tool wear or significant changes in contact conditions during the process.

On the other hand, isolated force peaks above the average value, as well as occasional drops, were identified, particularly a significantly lower value recorded at the end of the acquisition. These events suggest transient conditions possibly associated with specific moments of the pressing cycle, such as startup or shutdown, load relief, or measurement system interference. The presence of these points reinforces the importance of statistical analysis and adequate signal filtering for a more accurate interpretation of the actual process behavior.

Overall, the results confirm the capability of the experimental system to capture real variations in stamping force, enabling the identification of both steady-state regimes and relevant transient events. This information is essential for validating the theoretical and numerical models developed in the thesis and provides a basis for future comparative analyses under different process conditions.

The monitoring results expressed in tons indicate that the press operated predominantly within a narrow loading range, close to 260 tons, throughout the analyzed interval. This concentration of values indicates consistent stamping behavior, with satisfactory repeatability between observed cycles, which is desirable in industrial serial production environments.

The force oscillations observed in the graph are relatively small compared to the mean load value. This low dispersion suggests good operational stability of the system, with no evidence of progressive force increase or decrease that could indicate excessive tool wear, alignment problems, or significant variations in the properties of the processed material.

Localized force peaks slightly above the average, as well as small momentary drops, were also observed. These behaviors may be associated with specific events during the pressing cycle, such as changes in material resistance during deformation, variations in tool–sheet friction, or dynamic responses of the press mechanical system. The presence of these peaks reinforces the importance of continuous monitoring to identify conditions outside the ideal operating regime.

Another relevant result is the absence of severe instabilities in the force signal. No abrupt variations or erratic behavior were observed that could compromise process integrity, indicating that the press control system and the experimental setup operated under appropriate conditions during the monitored test.

Real-time data visualization combined with continuous force recording enables a more in-depth analysis of process behavior, allowing the identification of operational patterns and comparison between different operating periods. This type of result is particularly useful for future applications involving statistical process control and predictive maintenance strategies.

Finally, the results demonstrate that the developed system is capable of providing reliable information on stamping force, contributing to the understanding of press mechanical behavior and to the validation of the analyses proposed in this thesis. These experimental data constitute an essential element for discussing the effects of operational parameters and for improving real-time monitored stamping processes.

3.3 Experimental validation by comparison with real press data

The experimental validation of the developed system was performed through direct comparison between the force values obtained by the proposed monitoring device and the actual values provided by the press native system during the stamping process. For this purpose, a third column was incorporated into the data spreadsheet containing the real applied force values, recorded simultaneously with the device measurements, enabling point-by-point comparison over time.

Data analysis shows that although a systematic difference exists between the values measured by the device and the real press values, both exhibit coherent temporal behavior, with variations following the same trend throughout the process. When the press records an increase in applied force, the device also shows a corresponding increase, and the same occurs for localized reductions, indicating that the developed system adequately captures the stamping process dynamics.

The comparison revealed an average systematic difference of approximately 10 to 20 tons throughout the stamping cycle. This discrepancy can be attributed to factors such as different measurement point locations, differences between the instrumentation methods adopted by the industrial equipment and the proposed device, internal press

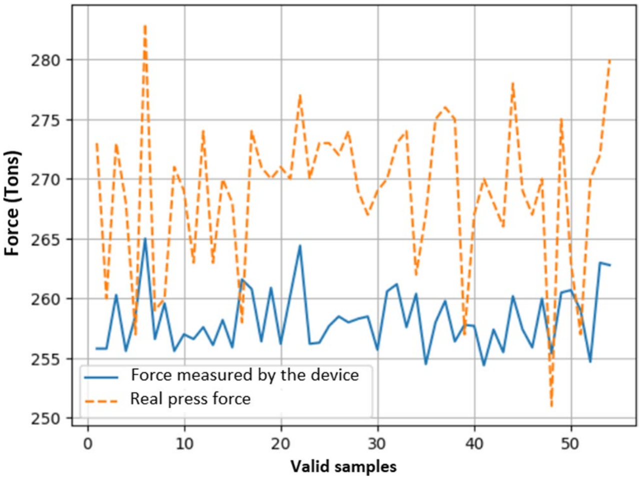


Fig. 14 Comparison between force measured by the device and the actual force of the press

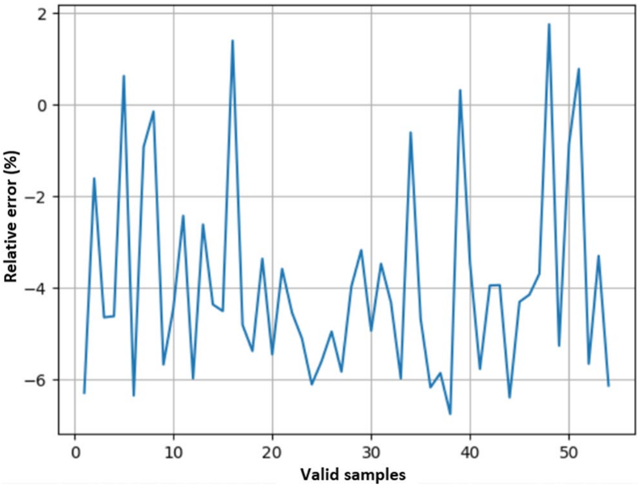


Fig. 15 Relative error between the force measured by the device and the actual force of the press

calibration, and possible mechanical losses along the force transmission chain to the instrumented point.

Despite this absolute difference, high temporal coherence between the signals was observed, with similar dynamic behavior and consistent identification of load peaks and regions of higher mechanical demand. The analysis of relative percentage error indicated that most values remained between approximately −2% and −6%, a range considered acceptable for indirect measurements in real industrial environments. These results demonstrate that the developed system is suitable for reliably representing the dynamics of the deep drawing process, fulfilling the objective of monitoring and diagnosing press mechanical behavior, even without direct access to the machine's internal measurement system.

The Fig. 14 presents the superposition of the force values measured by the developed device and the real values provided by the press system, considering only valid samples where both data sets are available, allowing direct and continuous comparison of force behavior throughout the stamping process.

Despite absolute differences, the data comparison shows that the device presents good correlation with real values, particularly regarding the identification of load peaks and regions of greater mechanical demand. In several instances, especially around higher force levels recorded by the press, a proportional response of the developed system is observed, reinforcing its capability to monitor actual process behavior without direct access to the industrial equipment's internal system.

The consistency between variations observed in both data sets indicates that the device is suitable for monitoring, diagnosis, and stability analysis applications in the stamping process. Rather than reproducing the exact absolute force value indicated by the press, the system efficiently captures force behavior over time, which is a key parameter for evaluating process performance and equipment operational integrity.

Thus, the comparison between measured data and real press values experimentally validates the proposed methodology, demonstrating that the developed system can faithfully represent stamping process behavior. This validation strengthens the reliability of the presented results and highlights the potential application of the device as an independent monitoring tool, especially in contexts where direct access to machine internal data is limited or unavailable.

The Fig. 15, shows the relative percentage error between the force values obtained by the proposed monitoring device and those provided by the press system, considering only valid samples. The error remains within a controlled range, indicating stability and reliability of the developed system.

Most error values are concentrated between approximately −2% and −6%, which is fully acceptable for indirect measurements in real industrial environments, indicating that the device slightly underestimates absolute force values relative to the press system. No increasing error trend is observed throughout the samples, indicating metrological stability of the developed system. Isolated points with error close to zero or slightly positive demonstrate good local agreement between the systems.

The Fig. 16, presents the correlation graph between the force measured by the developed device and the real force provided by the press system during stamping. A significant dispersion of points around the linear fit line is observed, resulting in a coefficient of determination $R^2 = 0.1104$. This value indicates low direct linear correlation between the signals, which was expected due to structural differences between the measurement systems.

The low coefficient of determination does not indicate failure of the monitoring system but reflects the structural

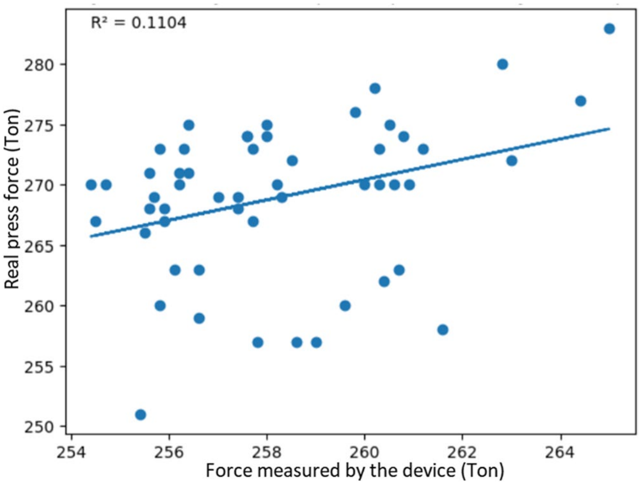


Fig. 16 Correlation between force measured by the device and actual force of the press

and metrological differences between the measurement methods employed. The developed system is not intended to reproduce the absolute force value indicated by the press, but rather to capture the temporal dynamics of loading, identifying peaks, steady regimes, and transient variations, which was consistently achieved throughout the tests.

The press system provides values internally processed by the industrial controller, while the developed device performs indirect mechanical effort measurement through externally mounted load cells. Thus, the signals represent correlated but not metrologically equivalent quantities, explaining the observed dispersion.

Nevertheless, joint analysis with temporal trend and relative error graphs demonstrates that the device can track actual force behavior during the process, with coherent variations and controlled percentage error. Therefore, the proposed system is suitable for monitoring, diagnostic, and stability analysis applications in real industrial stamping environments.

3.4 Qualitative thermographic analysis of the stamping process

To complement the analysis of mechanical loads identified from the force curves, a qualitative evaluation of the thermal behavior of the process was conducted using thermographic images acquired with a FLIR camera. The images illustrate the temperature distribution on the cap during different stages of the deep drawing process.

In Fig. 17, a maximum temperature of approximately 86.9 °C is observed, concentrated in the peripheral regions of the part, while the central region presents temperatures close to 31.5 °C. This center-to-edge thermal gradient is characteristic of deep drawing operations, in which friction between the sheet metal and the tooling, combined with localized plastic deformation, results in higher energy dissipation at the edges.

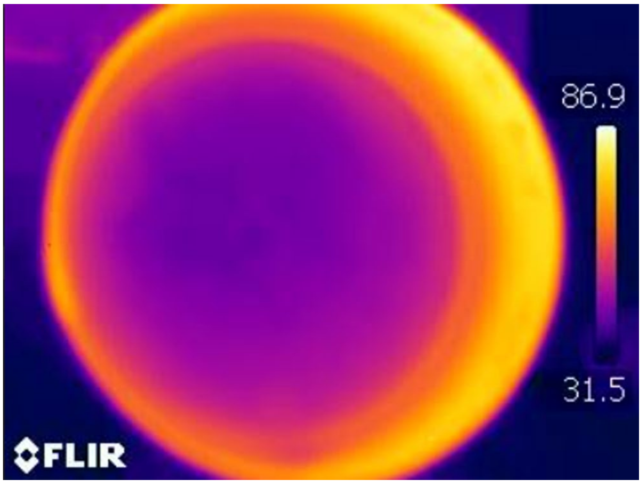


Fig. 17 Thermographic image acquired during the cap manufacturing process

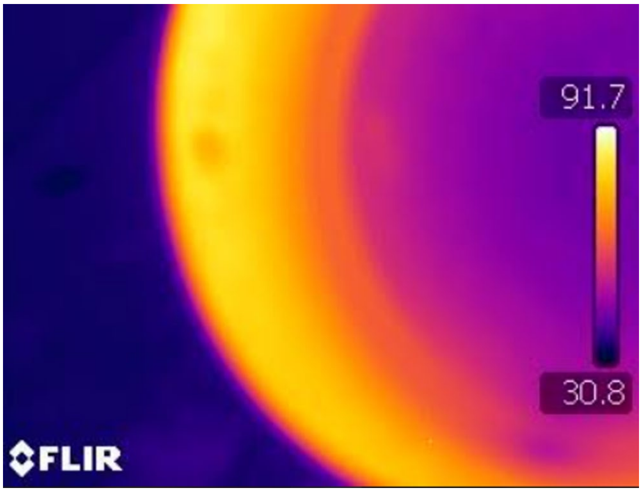


Fig. 18 Thermographic image acquired during the cap manufacturing process

The Fig. 18 shows an increase in the maximum temperature to approximately 91.7 °C, while maintaining thermal concentration in the peripheral regions. This behavior suggests an intensification of friction and mechanical loading during the intermediate stage of the forming process. In Fig. 18, the maximum temperature reaches approximately 93.3 °C, confirming the trend of thermal accumulation throughout successive forming cycles, without significant changes in the overall thermal gradient pattern.

Although the thermographic analysis is not directly integrated into the force acquisition system, the obtained results qualitatively reinforce the regions of higher mechanical demand identified by the force curves, contributing to a more comprehensive understanding of the deep drawing process.

3.5 Integration of results and perspectives for industry 4.0

The integration of results obtained from the force monitoring device with thermal and microstructural analyses highlights the potential of the developed system as a decision-support tool in industrial environments. Continuous monitoring of the applied force during the stamping process enables real-time identification of process variations, supporting the implementation of predictive maintenance strategies and quality control actions.

In this context, the proposed device aligns with Industry 4.0 principles by enabling the digitalization of critical information from the mechanical forming process. The combined analysis of force, temperature, and microstructural condition opens perspectives for the development of more robust predictive models, contributing to the optimization of the deep drawing process and to increased industrial reliability and competitiveness.

In Fig. 17, which presents the thermographic image obtained using the FLIR camera, reveals a temperature distribution with maximum values close to 86.9 °C, concentrated at the edges of the part. This thermal concentration is characteristic of deep drawing operations, in which peripheral regions experience higher friction between the sheet and the tooling, resulting in localized heating. Such behavior is directly related to the flow stress of SAE 1008 steel, whose plasticity favors energy dissipation in the form of heat.

The central region of the part exhibits significantly lower temperatures (around 31.5 °C), indicating reduced mechanical loading at the center during the process. This center-to-edge thermal gradient is expected in deep drawing operations, as plastic deformation is concentrated in the transition radius and in regions of higher contact. The preservation of this gradient indicates that the load distribution is being adequately managed by the tooling.

From an Industry 4.0 perspective, real-time recording of this thermal variation, combined with force monitoring provided by the instrumented press, offers valuable insights for predicting tool wear and potential process failures. The thermographic analysis confirms the relevance of infrared cameras as effective tools for quality control and process optimization in stamping operations.

In Fig. 18, a higher maximum temperature of 91.7 °C is observed, again concentrated in the peripheral regions of the cap. This increase relative to the previous image suggests intensified friction and energy dissipation, possibly associated with higher material loading during the intermediate stage of forming. The results indicate progressive heat accumulation in both the tooling and the material.

The central region remains at significantly lower temperatures (approximately 30.8 °C), preserving the thermal gradient previously identified. This behavior reinforces that most of the mechanical and thermal loads occur in the direct contact zones between the die, punch, and sheet metal. The temperature difference of nearly 60 °C between the center and the edges highlights the influence of friction and sheet thickness on energy dissipation.

From a technological standpoint, analysis of thermal evolution enables the identification of critical heating zones that may, over time, compromise tool life. Continuous monitoring of this variable can therefore support the development of lubrication strategies, coating selection, and adjustments to operational parameters aimed at improving process efficiency.

The Fig. 19 presents an even higher thermal level, reaching approximately 93.3 °C in the peripheral regions. This result confirms the tendency of heat accumulation in subsequent stages of the deep drawing process, indicating that increased localized deformation intensifies sheet–tool friction. This behavior highlights the central role of thermal dissipation as a relevant process control variable.

The central region of the part maintains temperatures close to 30.4 °C, reproducing the previously observed center-to-periphery thermal gradient. The consistency of this temperature difference suggests that deformation remains predominantly localized in the outer regions, which is coherent with the geometry of the gas cylinder cap and the operating conditions imposed by the 500-ton press. This consistency is indicative of process repeatability and material behavior stability.

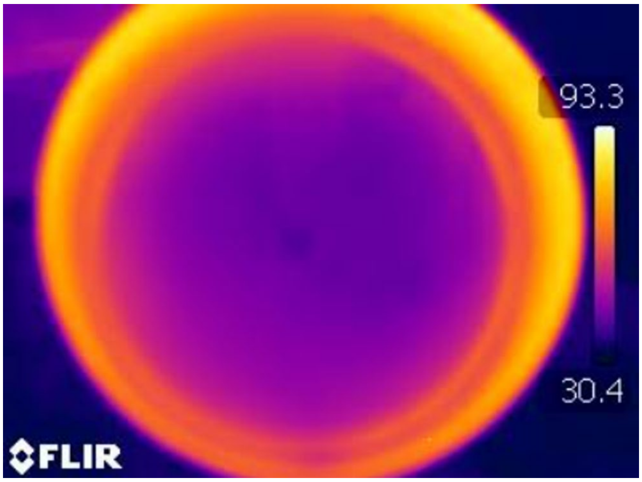


Fig. 19 Thermographic image acquired during the cap manufacturing process

Table 2 Comparison of thermographic images acquired with the FLIR camera

Figures	Minimum temperature (°C)	Maximum temperature (°C)	Main observations
Figure 16	31,5	86,9	Pronounced center-to-edge thermal gradient; higher peripheral heating.
Figure 17	30,8	91,7	Increased edge temperature; intensified sheet–tool friction.
Figure 18	30,4	93,3	Greater heat accumulation; stable center-to-periphery thermal gradient.

The thermographic analyses of the three images were compiled in Table 2, highlighting the formation of characteristic thermal gradients during the deep drawing process of SAE 1008 steel. In Fig. 16, a maximum temperature of 86.9 °C is observed at the edges of the cap, while the central region remains at 31.5 °C. This difference confirms that peripheral regions experience higher friction and plastic deformation, being responsible for greater energy dissipation in the form of heat.

In Fig. 18, the maximum temperature increases to approximately 91.7 °C, suggesting an intensification of the sheet–tool interaction during the intermediate stage of the process. The thermal increase observed at the edges indicates a progressive concentration of stresses and an increase in deformation effort, which may directly affect the local microstructure by increasing dislocation density and promoting strain hardening. The central region of the part, however, remains relatively stable, reinforcing the localized nature of the deformation. Finally, Fig. 19 records the highest temperature, reaching approximately 93.3 °C. This increase demonstrates heat accumulation at the edges without a significant change in the center-to-periphery thermal gradient, which remains essentially constant. From an industrial perspective, this analysis suggests that the process conditions are reproducible; however, it also reveals critical heating zones that, if not properly controlled, may compromise tool life and increase the occurrence of surface defects in the formed material. Therefore, thermographic monitoring combined with press instrumentation represents an essential tool for process control within the context of Industry 4.0 in controlling the stamping process.

4 Conclusions

The main objective of this work was the development and analysis of an experimental system for monitoring the applied force in the deep drawing process of gas cylinder caps, with emphasis on press instrumentation and data acquisition relevant to process control and to the understanding of mechanical forming behavior. The research was conducted in accordance with Industry 4.0 concepts, seeking to integrate sensing, signal acquisition, and data analysis applied to manufacturing.

Initially, the deep drawing process of AISI 1008 carbon steel—widely used in gas cylinder manufacturing—was analyzed considering its mechanical and metallurgical characteristics and its high formability. This analysis enabled the understanding of the predominant plastic deformation mechanisms and the factors that directly influence force distribution and heat generation during the forming process.

As the main experimental contribution, this study presents the characterization of the real stamping force behavior in an industrial press through an independent real-time instrumentation and monitoring system. Unlike approaches based exclusively on nominal values or internal machine signals, the developed system enabled continuous force data acquisition during actual press operation, allowing the identification of stable regimes, transient variations, and load peaks throughout the process. Validation through direct comparison with force values provided by the press demonstrated that the device is capable of reliably reproducing the process dynamics, offering a novel experimental approach for analysis, diagnosis, and monitoring of stamping processes that has not been consistently reported in the analyzed literature.

From an experimental standpoint, thermographic measurements were performed at different stages of the stamping process, enabling the identification of characteristic thermal gradients between the central and peripheral regions of the caps. The results revealed temperature concentration at the edges of the parts, associated with increased sheet–tool friction and intensified plastic deformation in these regions. The repeatability of the observed thermal gradient indicates process stability and adequate load transfer by the tooling, reinforcing the reliability of the measurements obtained.

Regarding the development of the monitoring device, experimental verification of the press analog output was performed using an oscilloscope, which was a fundamental step for signal validation and for defining the data acquisition strategy. This step confirmed the feasibility of using the machine's analog signal as input to the instrumentation system, enabling its subsequent conversion into applied force values during the stamping process.

Due to the absence of a measurable signal on the RS485 interface, it was concluded that this communication channel was not suitable for acquiring the data required for the development of the proposed device. Consequently, the use of the analog output from the load cells was adopted, whose direct measurement and subsequent signal conditioning enabled reliable implementation of the force acquisition and monitoring system during the gas cylinder stamping process.

The results obtained at this stage demonstrate that press instrumentation and process signal acquisition constitute effective tools for understanding the mechanical behavior of deep drawing. The thermal and mechanical data show high potential for process monitoring, identification of critical conditions, and support for decision-making in industrial environments. The results also indicate the potential for integration of these variables, although direct quantitative correlations are beyond the scope of this study.

Therefore, it is concluded that the proposed system represents a relevant contribution to the monitoring and control of the deep drawing process of gas cylinders, establishing a solid foundation for the incorporation of real-time force data. The continuation of this research, including further analysis of the results obtained with the developed device, will allow consolidation of correlations between applied force, thermal behavior, and microstructural changes, further expanding the scientific and technological contributions of this work.

Finally, this study contributes to the advancement of knowledge in the field of mechanical forming and process instrumentation, providing technical support for the development of intelligent monitoring systems applicable to Industry 4.0, with potential impact on improving quality, productivity, and reliability of industrial stamping processes.

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Data availability All data generated or analysed during this study are included in this published article. Additional raw data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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