In Situ Calibration Algorithm to Optimize Energy Consumption in an Automotive Stamping Factory Process

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Abstract: The world's large factories in all sectors consume a great deal of resources, either raw materials or energy, to develop their products. Saving resources can have a positive impact on the sustainable development of the planet. Automotive manufacturers are a clear example of how to save by investing resources in improving technologies and optimizing processes. This article focuses on one of the most common processes in the automotive sector: the stamping process. For the optimization of this process, previous simulations are usually carried out in order to define the optimal parameters and which should only be applied for a correct operation. The real circumstances of the plant show there is a large discrepancy between the parameters obtained by simulation and the real process because of the difference in material properties, lubrication, press operation, etc. The solution is that the operators must adjust the parameters a posteriori and the only criterion to follow is obtaining the right quality of the part. In many cases, the parameters are well above the ideal. This article presents some algorithms used in order to perform an in situ calibration of the stamping presses to find the press parameters that, guaranteeing the quality of the part, allow to adjust the energy consumption to the minimum. At the end of this article the experimental results from this in-situ calibration process and the energy savings are shown.

1 INTRODUCTION

The stamping process consists of applying a force on a sheet of reduced thickness (approximately 1mm) with moulds designed according to the geometry of the part to be manufactured. The main mechanical characteristic that must be taken into account to obtain a correct shaping of the part is the material elastic limit. If the parts are of large dimensions, therefore so must be the dies used. That is, the larger the die, the greater the weight to be moved through the press, being able to weigh up to 30 tons both the upper and lower die. Displacing these large moulds and properly shaping materials such as steel or aluminum requires the use of industrial presses with high workforce capacity, that is, for example when forming larger parts such as a side, larger presses will be needed as compared to manufacturing small parts such as door reinforcements.

Regarding the manufactured parts, the fundamental priority in the plant is to avoid passing defective parts to the following assembly processes, since a defective part in the subsequent processes increases the cost of the losses. For this, comprehensive quality controls are carried out at the end of the line where we can verify whether the product is suitable or not. In the event of a change in the quality of the product, adjustments are made to the process to verify that with the parameters entered the parts are within the quality margins in order to continue producing normally. This is a work that requires great knowledge since in the stamping process more than 40 different variables are involved, some of them are more important than others but just a small modification in one of them can cause quality defects, whether they are wrinkles, breaks, stretches, etc. And these variables are both due to the type of materials and the sheet thickness, the surface roughness, the amount of lu-

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bricant used, and the anisotropy and elasticity among others, as well as due to the equipment where wear in the die, mismatch in parameters such as the regulation or the stamping pressure of the material among others may happen.

To all this we must add the day-to-day work of an automotive plant, where it is essential to have the ability to be flexible and dynamic to adapt to the demand required at all times. In the stamping plant at Ford Spain facilities we have a large number of lines of different capacities, which allows us to have a great adaptation to the demand required. There are a large number of car chassis parts manufactured in the factory for the five models that are currently being made, these may undergo changes in the manufacturing standards, either by the type of material, geometry of the part, line change or other factors. Therefore, try-out tests are carried out for a new adjustment and to ensure that the quality of the product during mass manufacture is correct.

The tests carried out in the try-out procedure for the new adjustment consist of modifying the manufacturing parameters until reaching the most optimal point of resources use, both equipment and material. For example, adjustments are made to the working parameters of the press in the calibration to control the pressure with which the part is made, parameters of the pressure made in the press are also adjusted to control the amount of material drawn into the die in order to ensure no cracks occur due to excess stroking or wrinkles due to the lack of it. Other types of material can even be used instead of the one initially proposed, taking into account a different mechanical behaviour with which the work parameters must be adjusted again.

As for the characteristics of the presses we have in the plant, we can classify them in two groups, the mechanical and hydraulic presses. Most of the presses in the plant belong to the first group that includes, on the one hand, the cutting presses, which work at high speeds and perform the cutting of the coil in the blank parts that will later be used in the stamping process. We have also the stamping presses, characterized by being the largest ones, with which different operations are carried out, such as deep-drawing, cutting, drilling, bending and spring-back. These presses work at high levels of pressure due to the size of the moulds used for the aforementioned operations, especially those of deep-drawing. Within the mechanical presses we have two types, single-action and double-action. The latter are the ones that have been used for a long time for forming stamping parts, characterized by having two eccentric transmission systems in the press head. And on the other hand the single-action presses, which are more efficient, incorporating an intelligent hydraulic cushion at the bottom of the press including only one eccentric transmission system on the head.

Following the current trends in predictive maintenance, we intend to implement at plant level a monitoring system of the presses we have in the factory to find out their working status and be able to anticipate possible faults. It is known that the implementation of this type of industrial projects requires a great economic investment, but in our case, following the philosophy proposed by the Miniterms (Garcia and Montes, 2019), we intend to take advantage of the maximum of available sensors and taking into account the information that can be extracted from these develop new solutions to monitor the health of the equipment. This is a great advantage we have in the stamping plant, since most presses come equipped with a lot of sensors thus having at our disposal a lot of information at no extra cost.

The sensorization of the presses with strain gauges has been used for years to define pathologies of the equipment from different points of view, including diagnosing failures in the stamping process of both the equipment and the manufactured product (Koh et al., 1996). This can be done by applying different techniques to obtain information from measured data such as wavelets (Jin and Shi, 1999), relying on experiments (Jin and Shi, 2000) and even applying machine learning techniques by using neural networks (Bassiuny et al., 2007). Going a step beyond the detection of pathologies, process control systems have also been developed based on the graph obtained from the tonnage of each cycle (Zhou et al., 2015) or by finding variations in the lubrication of the process and wear of the die (Voss et al., 2017). Following the trends of internet of things in industry (IIoT) we now have a lot of available data in real time to model the process, as it has been done in this field by (Niemietz et al., 2020). Hence, in this paper we show the first insight we have obtained from the process and the advantages we are taking from the application developed for solving detected issues and optimizing the process from the point of view of energy consumption.

Optimizing the process to achieve energy savings is vitally important due to two major factors. One of them aims to achieve a sustainable development of the planet, reducing pollution and saving on available resources. And the second is the economic factor, since during the last year the price on the electricity bill at the factory has doubled the price and it is predicted that this upward trend will continue, thus these costs indirectly will affect the profit per car produced at the factory.

For the optimization of this process, previous simulations are usually carried out in order to define the optimal parameters which should only be applied for a correct operation. The real circumstances of the plant show there is a large discrepancy between the parameters obtained by simulation and the real process either because of the difference in material properties, lubrication, press operation, etc. The solution is that the operators must adjust the parameters a posteriori and the only criterion to follow is obtaining the right quality of the part. In many cases, the parameters are well above the ideal. Being able to have knowledge of a process and applygin in situ solutions is a trend that is increasingly used to develop technological solutions, as can be seen in (Grasso and Colosimo, 2017) and (Buchli et al., 2018). Hence, in this article presents some algorithms used to be able to perform an in situ calibration of the stamping presses in order to find out the press parameters that, guaranteeing the quality of the part, allow to adjust the energy consumption to the minimum.

The paper is structured as follows: in the next section we will explain previous considerations to take into account which are our purpose with the proposed methodology and in section 3 the following methodology to optimize the process will be shown. In the fourth section we will show a real case of how we have detected an abnormal function of the process and the modifications carried out. Finally, the conclusions and future works are proposed in section 5.

2 BACKGROUND

Together with the consequences that happen in an automotive plant as explained in the previous point, to this must be added the consumption of resources that is generated, due to raw materials, labour, and energy consumption. Therefore, for proper sustainable development and to be able to manufacture with the least possible impact on the environment, the aim is to optimize the use of available resources even by reusing materials that are classified as scrap due to the process.

What is sought in this research is to reduce the energy consumption of the stamping plant from the data extracted from the process in order to know how the presses are working with the different sets of dies and to look for an optimal point of the working parameters which ensures minimum energy consumption without affecting the quality of the manufactured material.

2.1 Previous Considerations

Throughout the stamping process, as mentioned above, the presses that carry out the Deep-Drawing process are the ones that can apply the highest pressure. Therefore, these are the presses with the largest electric motors and on which we will focus to develop our tool.

In stamping, two phases are required to get a correct configuration of the work parameters, in a first phase the simulation of the process is carried out with programs specifically designed for stamping. From which the working parameters of the press are defined by taking into account the design of the part and characteristics of the material. But due to the variations between the simulation and the real world, a second phase is required in which try-out tests are carried out in the plant by performing an adjustment of the equipment in order for the product to meet the quality requirements, in which the final process adjustments can vary with respect to those defined by the design.

The main properties of the material to take into account in the forming are the deformation the sheet undergoes in the different areas along its entire surface. Due to the non-linear plastic deformation characteristic of the deep drawing and the non-homogeneous material flow during the process, it is very difficult to control its efficiency.

$$E = \frac{\sigma}{\varepsilon} \quad (1)$$

In the forming process of a steel sheet there are several properties of the materials that are fundamental to take into account to achieve a correct deep drawing without causing defects. One of the possible defects is wrinkles which can be caused by several factors in the process, but mainly because the elastic limit of the material has not been exceeded and therefore it tries to return to its initial position.

To do this, a certain tension must be applied that allows exceeding the elastic limit of the material but without causing breaks or stretches that do not provide structural stability. Therefore, the result of the tension against deformation can be seen in the red zone in figure 1 where the material is in the hardening zone.

To obtain stamped product information, we are able to obtain the deformation (ε) of a stamped sheet to ensure that we will have no quality defects with the final configuration. The process consists of printing a mesh in the plate by electrolytic marking. Afterwards, the stamped part is taken to the laboratory and with a high-resolution camera, with 20 million pixels, photos are taken of the different areas to be analyzed, the example shown in figure 5 is the central beam of

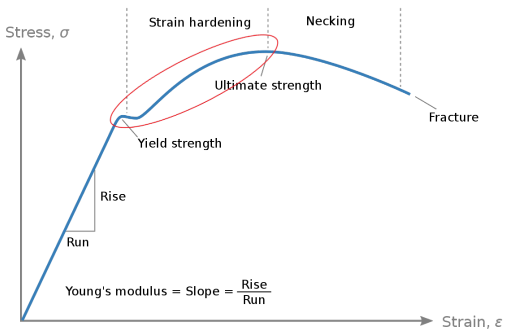

Figure 1: Stress–Strain Curve.

the measured part. Using the AutoGrid® software we can obtain an output of the FLD of the area analyzed with the strain of each node measured, showing the maximum strain ε_1 and ε_2 per node in the diagram with the bounds of the diagram previously defined for the specific material.

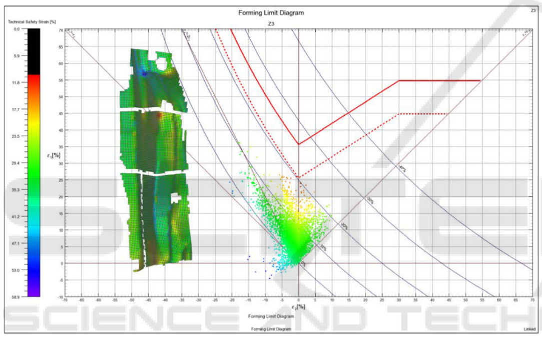

Figure 2: FLD of a Real Stamped Part.

According to this research development, once the working parameters are known in real time and the stamping process is understood in depth, the process will be optimized from the point of view of press work, where the least amount of energy resources is used for the shaping of the parts, we verify that the consumption of the electric motor of the press and the measured tonnage are directly related in a proportional manner. In the result section, we have verified this through real measurements of the process.

2.2 Previous Work

Real-time data monitoring is essential to know the status of the machine. By applying IIoT (Industrial Internet of Things) techniques we are able to receive a large amount of process information, the pressure made by the presses, pressures of the hydraulic and pneumatic groups, press movement activation time, speeds and positions of the different moving elements among others. Of these, a real-time application (Peinado-Asensi. et al., 2021) was developed based on the information obtained from the tonnage sensors so that we have been able to find out the quality of the press throughout the cycle in each and every press stroke during production.

In order to obtain information on the relevant process, an alarm sending system has been defined so that for each of the different parts of the car produced, we can store the press cycles that fail including detailed information on which press position said anomalous event has occurred. The reason why it has been made for each part is because depending on the geometry of the die the pattern of the gravity centre may vary considerably. We also have a parallel system used to control the press at all times, which warns us about how much it is deviating from normal functioning towards the limits of the press. We currently have these margins defined as shown in the picture below.

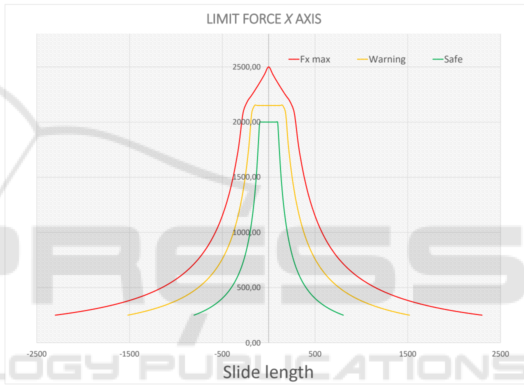

Figure 3: Health Monitoring Limits.

To validate that the tool worked as expected and the data received from the Gravity Centre were correct, a test was carried out with 4 columns mounted at the same height at the base of the press, then we unbalanced them by adding 1 mm thick sheets between the different columns and after shifting the gravity centre towards each of the sides, we found out that the results obtained coincided with what was expected, being able to determine that our system works as expected.

The value of the sensor has been taken for each press position to obtain the gravity centre and the equation shown below has been applied,

$$GC_j = \frac{\sum T_i D_i}{\sum T_i}, \quad i = 1, \ldots, 4, \quad j = 0, \ldots, 359. \quad (2)$$

Where T is the value of the tonnage sensor and D the distance from the rod foot to the centre of the press slide.

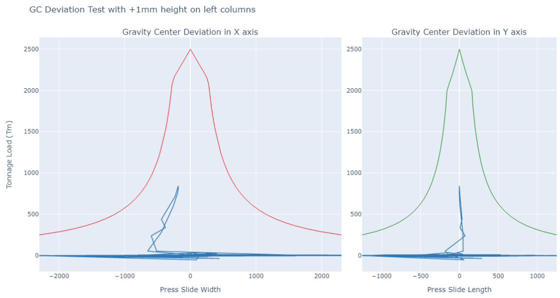

Figure 4: Gravity Center Graph.

3 IN SITU CALIBRATION ALGORITHM PROPOSAL

We have 3 critical variables that directly affect the energy transmitted by the flywheel to the eccentric transmission system and this energy of the flywheel is calculated as shown

$$E = \frac{1}{2} \cdot J \cdot \omega^2, \tag{3}$$

where J is the inertia transmitted by the flywheel and ω is the angular speed at which the flywheel rotates. In this case the inertia is fixed since it depends directly on the geometry of said flywheel where the mass and the radius are always the same, therefore the greater the energy requirement, the greater the speed of rotation transmitted by the electric motor of the press by means of a pulley transmission system.

One of the parameters evaluated as critical with respect to the energy required for the press movement is the die weight, which depending on the part produced can be higher or lower, between 5 and 30 tons approximately. The second parameter is the compensation pressure, which consists of two large volume pneumatic cylinders in which the pressure is adjusted depending on the die weight in order to help the press raise the slide and die at the end of the cycle. And third, the adjustment of the press slide, the lower the height of the slide, the greater the pressure in the die to exert a travel of the upper die and therefore greater energy will be needed to be transmitted from the inertia flywheel.

Therefore, the control algorithm proposed to adjust the working parameters of the press and ensure that the energy consumed is minimal is as follows.

We can see there are two variables that can be modified to optimize the power consumption, the adjustment of the slide and the pressure of the compensation cylinders.

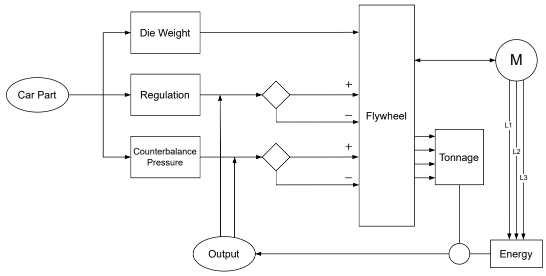

Figure 5: In-loop Control Diagram.

3.1 Slide Adjustment

On the one hand we have the slide adjustment, this parameter is very sensitive and critical in terms of part quality. Since modifying tenths of a millimetre, both upwards and downwards, significant quality defects, wrinkles or breaks may appear, respectively, thus turning the product into scrap. This parameter will be modified by try-out tests in the event that the press pressure is detected outside the designed work value. A real case of this setting will be shown in the next point.

Being a parameter directly related to the force exerted by the press, with the measurement of the tonnage sensors we can obtain information on whether the adjustment is adequate or programmed at a value that can damage the mechanical elements of the press by performing a force greater than necessary.

The way to proceed will be as follows, starting from a tonnage detected as anomalous in the sense of exceeding the design working conditions. Tests will be carried out by modifying the adjustment in half a millimeter each time. Then a stamping cycle is carried out verifying, on the one hand that the quality of the produced part has not been affected and on the other hand, the resulting tonnage value, in case of being able to reduce the tonnage, this process will be repeated until reaching a value of the slide adjustment which does not cause wrinkle or springback defects in the material.

3.2 Counterbalance Pressure

On the other hand, we have the compensation, so for this variable the energy consumption in a cycle will be measured for different pressure values. With the values obtained, we can proceed as explained below.

As explained above, this is an auxiliary system that exclusively affects the operation of the equipment, which will cause two cases of mismatch. On the one hand, the manufacturer provides us with a list of compensation pressure values depending on the upper die weight. On several occasions this value has been modified with readjustments after a fault, for example, or external factors that cannot be controlled. In some cases, depending on the consumption, we will need to optimize the value required by the manufacturer, which may not be the most optimal one. The following methodology is therefore proposed for adjusting the compensation value. To achieve the minimum energy, the gradient descent method is applied for n iterations

$$x_{n+1} = x_n - \alpha \nabla f(x_n), \tag{4}$$

for a known function $f(x)$ that will give us the energy value with regard to a pressure value, but the problem is that from our measurements we cannot define an exact function for the behaviour of the measured values. To do this, we are going to obtain an approximate function $p(x)$ by using the method of approximation by polynomials of degree n,

$$p(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n, \tag{5}$$

where having n points we will need $n+1$ measurements, being

$$p(x) \simeq f(x). \tag{6}$$

At this point we must obtain the values of $a_0, \ldots, a_n$ by solving the system of n equations with n unknowns that we would have left, being n the number of total measurements made. Once the function is obtained, the gradient descent method is applied to obtain the lowest energy value with respect to the compensation, obtaining the optimal value for the process and adjusting it online according to our control system shown in figure 5.

4 EXPERIMENTAL VALIDATION

For the measurement of the energy consumed with the different working parameters, the Fluke 438-II Power Quality and Motor Analyzer equipment has been used, connected to the output of the electric motor drive as can be seen in figure 6, being able to measure the energy consumed directly by the electric motor.

4.1 In Situ Slide Regulation Calibration

Among the available lines in the stamping shop, there are two twin lines to manufacture big car body parts

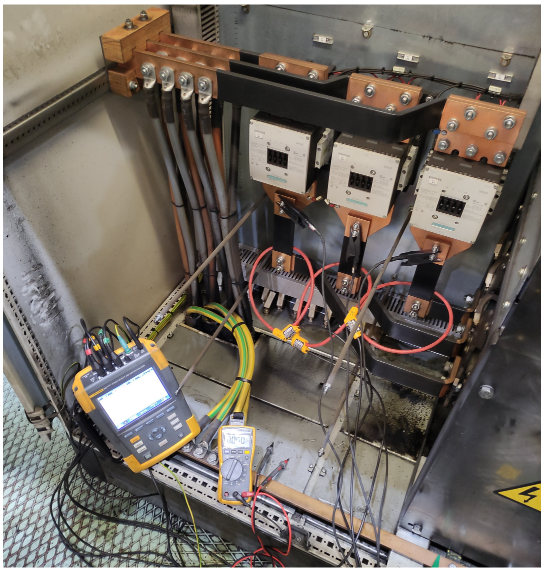

Figure 6: Energy Measurement.

with 2500 tons of capacity in the deep drawing operation, where the gravity centre system is currently monitoring data. During the period the app has been working, no signs of malfunction or imbalance have been found in the slide. There is an alarm system that warns us about the number of strokes and which press position the imbalance is taking place. There are two ways of reading the information of the gravity centre, a weekly report with the productions status of each die and a real time dashboard where it has been counted the number of times our security limits are exceeded. So we can monitor the working status of the machine all the time.

Until now, all the monitored parameters mentioned before have been correct without having any abnormal behaviour, but there is still other important limit to check: the working load limit of the press. The press manufacturer recommended not to exceed at least 80% of the limit force, as those machines are designed to work with 2500 tons maximum, but the advised number should be 2000 tons to ensure a correct working status.

Our alarm system detected a part that was being manufactured with 2300 T as can be seen in figure 7, an unusual load that had not been previously recorded. We checked it and found out the following events: the part produced was the roof of the Ford Transit van in its long version shown in 8, when manufacturing this part one of the largest forming dies available in the plant was used.

It was shocking at first because a simple geometry car part should not cause problems unless something strange happened, but everything seemed normal. So

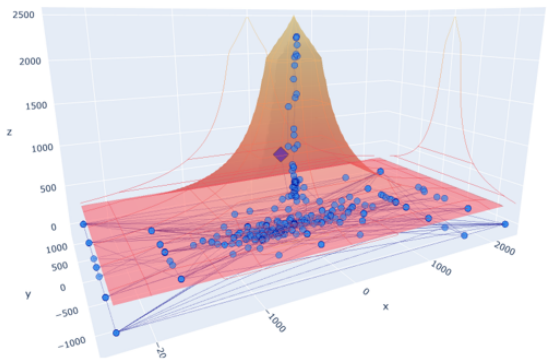

Figure 7: Gravity Center Graph.

after making some research to figure out what would have caused this event, we realized that the die set was changed from one line to another, that is, new parameters were input in the stamping line and clearly some error would have caused this.

Figure 8: Car Body Part - Roof.

Comparing working parameters from one line to another, before the tonnage data monitoring the load was around 1500 tons. So try-out jobs were organized to modify parameters to optimize the process. Table 1 shows the measured values before and after the in situ adjustment.

Table 1: Working parameters comparation.

	PRE	POST
Tonnage (T)	2292	1618
Counterbalance (bar)	7.4	7.4
Slide reg. (mm)	1371.5	1373.5
Energy (kWh)	416	359

Where you can see that the tonnage has been reduced by about 700 tons by modifying the adjustment only $2\,mm$ and the energy consumption in one hour of work has been reduced by 57 kWh.

4.2 In Situ Counterbalance Adjustment

The test for compensation was performed on a smaller press as compared to the anomaly presented in the previous case. In this case we used a double-action mechanical press with a maximum capacity of 1500 tons, where smaller parts are manufactured as compared to those used in the presses described in the previous point. Here we have the peculiarity that for each type of die, because of the weight difference between them, different energy values will be obtained. Therefore we should repeat the process for each of the different car chassis parts manufactured.

The values shown in table 2 are the measurements for a press cycle showing the consumption for each of the pressures from 3 to 6 bars during several strokes. After measuring several strokes for a fixed pressure, the average Wh conpsumtion per hour was obtained.

Table 2: Working parameters comparation.

Measure	Pressure (bar)	Energy (Wh)
1	3	45
2	3.5	44.25
3	4	44.5
4	4.5	46.75
5	5	44.25
6	5.5	45.5
7	6	48.75

The function that defines the distribution of points should have a shape like the one shown below and it will be the one we need to look for, an approximate function $p(x)$.

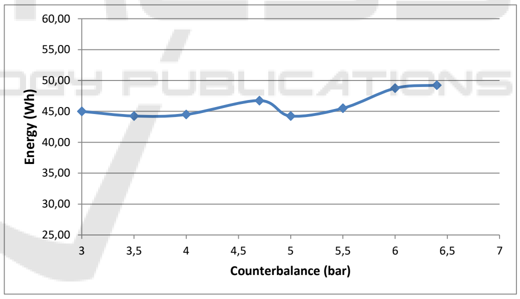

Figure 9: Couterbalance - Energy Graph.

To obtain the function that describes the behaviour of the consumption with respect to the pressure, we will apply the method of approximation by polynomials defined in equation 5, therefore we will have the following expression:

$$p(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 + a_6 x^6. \tag{7}$$

There is a system of 6 equations with 6 unknowns to solve in order to have the values of the parameters $a_0, \ldots, a_n$ and obtain the approximate function that will give us the energy consumption for a given compensation. The values obtained for this die are as follows;

$$a_0 = -2.0585 \cdot 10^4, \qquad a_1 = 2.9929 \cdot 10^4,$$

$$a_2 = -1.7837 \cdot 10^4, \qquad a_3 = \frac{67063}{12},$$

$$a_4 = -971, \qquad a_5 = \frac{1331}{15}, \qquad a_6 = -\frac{10}{3}.$$

Once the function is obtained, the gradient descent method is applied to obtain the lowest energy value with respect to the compensation, obtaining the optimal value for the process and adjusting it online according to our control system shown in figure 5.

5 CONCLUSIONS AND FUTURE WORKS

This article shows two in situ calibration techniques of stamping process parameters that allow to reduce the energy consumption of the manufacturing process. In-situ calibration methods are commonly used to adjust sensors or processes, which cannot be adjusted from the factory since the discrepancy between the ideal and actual situation is significantly different. This is the case of the stamping process where the values assumed in the simulation process and the reality of the process require the operators to make adjustments on the process and where it is common to find them oversized. The calibration algorithms proposed in this article make it possible to perform this calibration and achieve significant energy savings, as demonstrated in this paper. As future works, we will intend to generalize these in-situ calibration techniques to the rest of the presses and also other processes of the factory having the same problem.

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