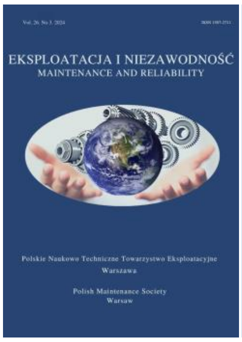

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 26 (2024), Issue 3

journal homepage: http://www.ein.org.pl

Article citation info:
Skardžius J, Nagurnas S, Skačkauskas P, Modernization of the stamping process using eddy current and load sensors in the manufacturing of automotive parts, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2024: 26(3) http://doi.org/10.17531/ein/189453

Indexed by:

Modernization of the stamping process using eddy current and load sensors in the manufacturing of automotive parts

Juras Skardžius[a,b] , **Saulius Nagurnas**[a], **Paulius Skačkauskas**[a,*]

[a] Faculty of Transport Engineering, Vilnius Gediminas Technical University, Lithuania
[b] LLC "Stansefabrikken Automotive", Lithuania

Highlights

- Experimental research on sensor technologies usage in the progressive stamping process.
- Experiments were conducted by applying eddy current and load sensors into existing tools.
- The obtained results offered a methodology that can be applied in manufacturing.
- The research provides developed opportunities for the use of sensors in production.

Abstract

In this research, an experimental study is presented, which extends the usage of eddy current and load sensors in progressive stamping tools to optimize and continuously monitor the stamping process. The purpose of the research was to automatically detect material scrap before it leaves imprints on the part and based on the sensor's readings, determine the optimal tool bottom position. The scrap thickness that needs to be detected was established in an experiment by visual evaluation of the result. To determine the optimal bottom position, a linear regression method was used, and the results were evaluated by part quality parameter. The research results consist of separate detection steps and the conclusion was made only after the serial type production. Overall results of scrap detection were influenced by the design of the existing tool. The bottom position detection consists of various readings interpretations and multi-step method descriptions. Based on the acquired results of both methods, implementing the in–die sensors was considered successful and applicable to new tools.

Keywords

manufacture of automotive parts, stamping, progressive tool, performance optimization, eddy current sensor, load sensor.

1. Introduction

1.1. Specifics of the sensors used in the progressive stamping process

Progressive stamping is a complex process that depends on more than forty different parameters, such as material properties, wear of matrices and punches, lubrication efficiency, and others [1, 2]. Obviously, even the most experienced operator cannot monitor and control all of these variables, so modern stamping presses are increasingly using a variety of sensors for this purpose. A comprehensive review of this topic is given by Ravindran and Peinado [3, 4]. The authors review various types of sensors, explain their operating principles, and discuss installation and application. Detailed information on these topics can also be found in the brochures of sensor manufacturers [5, 6]. More general, applied articles about using sensors in various companies and the benefits obtained from them are printed in the Stamping Journal [7–10] and other publications [11–13].

From a historical perspective, the primary function of sensors used in stamping was to protect the press and the tool

---

(*) Corresponding author.
E-mail addresses: J. Skardžius (ORCID: 0009-0006-1909-0132) juras.skardzius@stud.vilniustech.lt, S. Nagurnas (ORCID: 0000-0003-1413-4475) saulius.nagurnas@vilniustech.lt, P. Skačkauskas (ORCID: 0000-0002-2082-9372) paulius.skackauskas@vilniustech.lt,

installed in it from overloads [6]. Overloads are a common phenomenon in stamping, which can be caused by various reasons, such as a too-low position, raised waste, or inaccuracies in the material feeding system [14]. In such cases, the enormous force generated by the press can seriously damage both the press itself and the tool installed in it. To prevent this, all modern presses are equipped with systems that stop the press when the load reaches a set limit. This can be done using simple mechanical, hydraulic, or sensor-based systems, but nowadays, it is becoming increasingly common in hydraulic valves of presses controlled by proportional technology to be used. By adjusting parameters (the control signal waveform), it is possible to regulate and monitor the maximum pressure value, the start-up time, and the reaction time [15]. Modern single-stage proportional maximum valves are fast and accurate but to carry out tests to determine operational parameters directly affecting their dynamics in the system is required. Tests reduce the valve's response time and reduce its hysteresis and excess pressure associated with overloading the press system. The optimization of the design of proportional maximal (overload) valves by using advanced weighting functions and logic trees is possible [16]. However, these systems are not effective in monitoring overall load change caused by insignificant foreign body. The latter has the advantage of being able to stop the press and allow continuous monitoring the load level and draw conclusions about the state of the process from this.

Sensors designed to monitor the force generated by the press are probably best suited for this purpose, as they directly reflect the processes taking place during stamping. A comprehensive review of this is provided by Groche et al [17]. Depending on the presented research, the assumption could be made that by monitoring press tonnage, to monitor part quality is possible as well. Unfortunately, according to Li and Bassiuny [18], due to the complicated installation, the use of force sensors to monitor the press load is limited, so strain sensors are more often chosen for this purpose. The latter are cheap and suitable for monitoring both static and dynamic loads [1]. Several problems indeed need to be solved to judge from the signal of the deformation sensors about the changes taking place in the process, such as the wear of the tools or the instability of the material feed [19, 20].

The change in load caused by the aforementioned changes is very small compared to the total load on the press, so their detection is complicated. Sophisticated signal processing methods are used to solve this problem. For example, Zhou et al. [21] analyzed the possibility of using strain sensors installed to monitor the press load to detect errors and then move to the next stamping station. Using a method based on reoccurrence plots, the researchers successfully detected such events, although at first glance the load signal was virtually indistinguishable from the one obtained when the part was correctly moved. The authors' research conclusions suggested that press load signal could be used not only for process control but also for primary set-up. Another example is the study by Li and Bassiuny [18]. These authors draw attention to the low-strain signal-to-noise ratio and the transient nature of this signal, which makes it very difficult to extract useful information from it using traditional methods. As an alternative, the authors test the latent model, wavelet, and Hilbert-Huang transforms. The effectiveness of these methods is tested in the progressive molding of an automobile engine hood, during which piezoelectric strain sensors are used to detect incorrect tape feeding. Based on the test results, the authors conclude that the Hilbert-Huang transform is the most suitable for this.

Another problem, especially for progressive stamping, is that the press load signal is the sum of all the loads generated in the process. Therefore, even if a small deviation from the norm is successfully detected, it isn't easyto diagnose what, and at which step of the tool caused it. Jin [22] tries to solve this problem. The author claims that the total load signal can be divided into separate parts characteristic of only one or several steps. In the latter case, the probability of false detection increases, but it can be reduced by analyzing the specific stamping process. Such an analysis may indicate that the operating ranges of the steps with supposedly overlapping signals are so different that the probability that a change will occur in one of those steps is very small, or that if a change does occur, the signal change will be so small that it can be ignored. By evaluating such aspects, it is possible to exclude some overlaps and thus increase the reliability of the diagnosis. Force signal decomposition method hinted course for our further research.

As can be seen from the performed research, the press load signal can be used not only to protect the equipment but also to monitor more subtle changes in the stamping process. True, due to the relatively small, transient nature of the response caused by such changes, signal processing is complicated. In addition, the fact that the monitored load is the totality of all the loads generated in the process increases the probability of false detections, which reduces the reliability of the diagnostics. To avoid these problems, specific sensors installed to monitor a specific event or process are used.

In stamping, eddy current sensors are used for another typical process problem, misalignment of the strip in the tool by wide variations [23]. When such an event occurs, the stripper plate tilts, thus changing its distance to the fixed point. Monitoring this distance makes it possible to determine that a wider coil has entered the tool. Better results can indeed be achieved by combining eddy current sensors with force or acoustic emission (AE) sensors [24, 25]. These two groups of sensors are also widely used for punch and die wear monitoring and fracture detection.

1.2. Analysis of stamping process development possibility

As can be seen from the above examples, the use of various sensors in stamping, including progressive ones, is intensively researched. However, several unanswered questions remain. One of them is the optimal number of sensors and the most suitable mounting location in the die. Some authors believe that a company thinking about quality should install sensors under each die matrix [12]. In reality, doing so would be very difficult and not always logical for several reasons. First of all, installing sensors under each matrix would be expensive. Second, as controversial as it may sound, a large number of sensors can have a negative impact on system reliability. This is determined by several factors. First, sensors, like all devices, can fail. As an example, Garcia's review [25] shows that malfunctioning sensors can account for as much as eighteen percent of press failures. In addition, even a functioning sensor can become a problem due to spurious trips, which stop the process unnecessarily [26]. Unfortunately, the theory of system reliability shows that the number of such cases is directly proportional to the number of installed sensors. However, in a case study performed by Rong-Xing Duan et al. [26], an effective sensor placement method based on the reliability criterion in the presence of epistemic uncertainty was proposed. The authors additionally proposed an algorithm for the potential locations of sensors by using a diagnostic sensor model that was based on a sequence captured between sensor failures and the monitored component failures. Another factor affecting reliability is the fact that, to install the sensor, it is necessary to mill cavities and channels for the wires in the die, which negatively affects its strength properties. This is especially important when efforts are being made to produce lighter and cheaper tools [27], which means that, in the future, tools will have a lower margin, so not predicting where the sensor will be mounted in the design phase can lead to problems later, as each additional hole weakens it optimized structure. Another reason why there should be no rush to install sensors under every matrix is that every measurement is meaningful only if its results are used purposefully. Otherwise, it's a basic waste. Therefore, only as many sensors should be installed in the dies as are needed to obtain the desired result and only where the sensor can generate a reliable signal. Unfortunately, there is not much research done in this area.

Fifty useful tips on how and where to mount sensors are provided by Finnerty [29]. Sensors are crucial for detecting tool failure, measuring displacement, and detecting tool breakage and flaws in parts. Similar topics are also discussed by Ravindran and Su [3]. The authors examine how part quality and sensor signal are affected by variables such as material, lubrication, and press characteristics. Sensors and monitoring techniques in modern production represent a cost-effective investment to maintain part quality, production rate and reduce scrap and downtime. It is emphasized that usually, the main rule is to install the sensors as close as possible to the place to be monitored, because as the distance increases, the signal weakens and distorts, making it harder to detect. A different opinion can indeed be formed from the research conducted by Groche et al. on the use of force sensors in stamping [17]. The authors state that indirect measurement, when the sensor is installed further from the desired monitoring area, is more practical because it provides more opportunities to choose a place where it is easier and cheaper to install the sensor, where it weakens the die less and is less loaded by itself. The results of the tests carried out during the study show that in this case, it is possible to obtain a signal of similar quality as when measuring directly. However, the authors acknowledge that to improve accuracy, the location of the sensor must still be considered. In addition, special calibration may be required.

A study by Groche et al. [17] also confirms that sensors can have a negative impact on die reliability. In a specific case, experiments were carried out with force-measuring discs installed between the press table and the bottom plate of the die. The resulting gap allowed the bottom plate to bow, subjecting the die to a cyclic load that does not occur when the plate rests on the table with its entire surface. In addition, it was observed that the deflection of the plate absorbs some of the load, so the measurement shows a lower punching force than it actually is.

In the ideal case, the quality attributes of the part should be observed in the die itself, during their formation [30]. Thus, reducing the reaction time to possible inconsistencies to a minimum and tool wear monitoring possibility is enabled. It also could be linked to part and overall process traceability.

1.3. Research issues, purpose and established tasks

Based on the literature analysis (Chapters 1.1, 1.2), it could be said that after installing sensor technology in the stamping tool, autonomous or partially autonomous monitoring of process and part quality is possible, increasing the possibilities of traceability and shortening the time of decision-making. However, encountering many problems mentioned in Chapter 1.2.

This paper proposes two methods to extend sensor usage and improve process effectiveness by continuously controlling areas that mostly depend on the human factor. In progressive stamping, these areas are imprint detection on part (because a foreign body that appeared may have no noticeable impact on the press used tonnage due to its size) and tool bottom position set (because the tool bottom position is most often determined by the operator and his visual experience).

The purpose of the research covered in this article is to investigate the possibility of using sensor technology to detect imprints in a continuous process and determine the tool's bottom position.

The following research methods were proposed:

1. Foreign material body could be detected by eddy current sensors - the method relying on the distance measurement principle, that the foreign material body appeared should increase the measured distance from the tool bottom to the middle plate and send the signal to the system to stop the press.
2. Press load sensors could be used to determine the tool's bottom position - the method suggests that load rise dependence of the tool's lowest position could be determined by a clear tipping point before the load has been gradually growing and after then it starts to increase exponentially is illustrated in Fig. 1 and could be expressed in the following equation (1):

$$y = \alpha + \beta x, \tag{1}$$

where y is the established tool column load; α and β are line parameters; x is an intersection point of the lines.

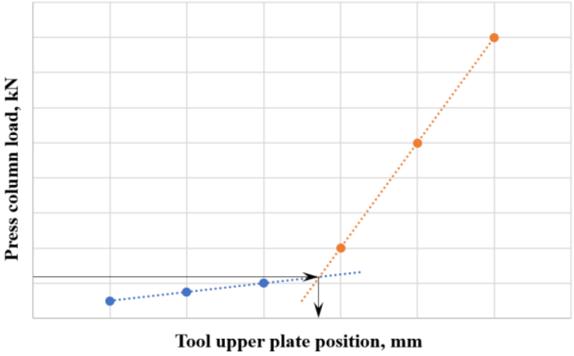

Fig. 1. Press load method application using the linear regression principle.

The following tasks were set to realize the raised methods:

1. Create a methodology for testing the sensors selected for the raised methods, while carrying out progressive stamping operation;
2. Install the aforementioned sensors into a progressive stamping tool intended for work in real stamping conditions;
3. Based on the testing methodology and the results of the experimental studies, analyze the obtained data, evaluate the work efficiency of the progressive stamping tool;
4. Analyze the results and present conclusions.

2. Experimental research methodology

For distance measurement in tool purposes, eddy current sensors, inductive sensors, and optical sensors could be used. Referring to the proposed first method and the planned practical use, it was decided to install two eddy current sensors, due to their resolution and measurement range, on stop blocks of the tool. The place and quantity of the sensors were chosen keeping in mind that the foreign material body may be thinner than the material used for stamping and assessing the risk that it may appear in any part of the strip. Eddy current sensors were installed on the tool stop blocks due to the sensors' technical possibilities. The technical data of the eddy current sensors are presented in Table 1, and their installation locations are shown in Fig. 2. The eddy current sensors reading was connected with shaft position sensor readings. The work area dimensions of the tested tool were 1250 mm in length and 870 mm in width.

Table 1. Technical specification of the eddy current sensor.

Characteristic	*Value*
Manufacturer	TRsystems GmbH, Division Unidor
Model	WSD S2/10MF
Measurement range	0 – 2 mm
Linearity	± 0.12 mm
Repeatability	0.02 mm
Resolution	< 0.001 mm
Response time	< 1 ms
Linearity deviation	+/- 12µm

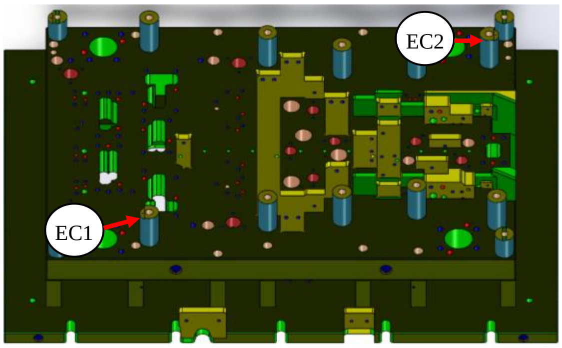

Fig. 2. Sensor's EC1 and EC2 position.

The shaft position sensor CEV58S–00117 was connected to the press. The technical data of this sensor are presented in Table 2.

Table 2. Technical specification of the shaft position sensor.

Characteristic	*Value*
Manufacturer	TRsystems GmbH, Division Unidor
Model	CEV58S–00117
Resolution	≤ 33 bits
Measurement count	≤ 256000

For the second method, the press load sensors JZT1 and JZT2 were mounted on the columns of the press diagonally opposite each other (see Fig. 3) and calibrated so that the sum of their readings was equal to the force generated by the press. The technical data of these sensors are presented in Table 3. Opposite columns were chosen to avoid load reading loss due to diversion risk.

Table 3. Technical specification of the load sensor.

Characteristic	*Value*
Manufacturer	TRsystems GmbH, Division Unidor
Model	JZT 127/S–MS

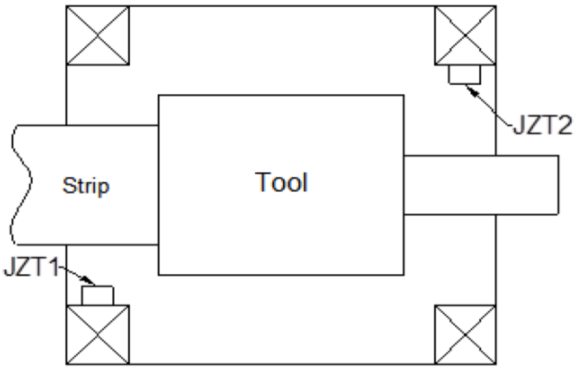

Fig. 3. Sensor's JZT1 and JZT2 position.

Important to mention that sensors used for both methods were connected to the data processing and control system compactPRESS smartLINE. The key element is an intelligent controller that continuously monitors and analyses the signals of the sensors connected to the system to protect the press with the tool installed in it and ensure an optimal and controlled production process. Other elements of this system are described in Table 4, while their interconnections and practical application in a stamping line are shown in Fig. 4.

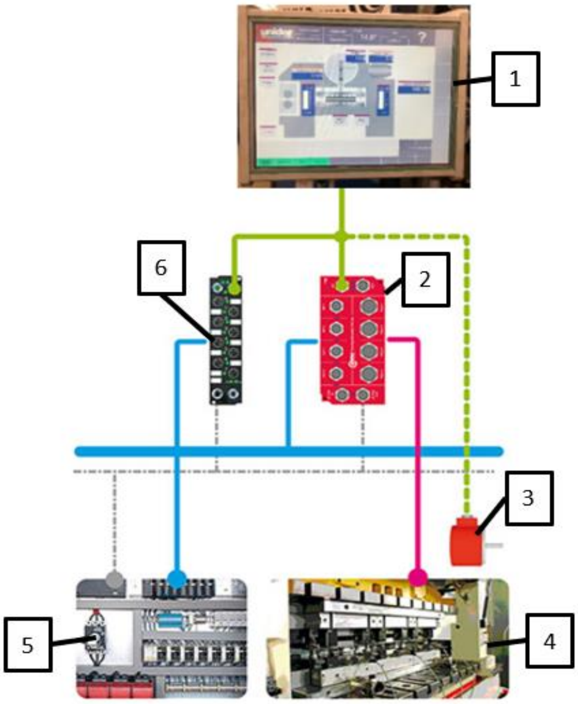

Fig. 4. Sensor's Communication scheme of the sensor's system: 1) display screen; 2) press sensor's connection adapter; 3) additional input; 4) press sensor; 5) tool sensor; 6) tool sensor's connection adapter.

Table 4. Technical data of the data processing system.

Characteristic	*Value*
Manufacturer	TRsystems GmbH, Division Unidor
Model	UNiDOR compactPRESS smartLINE
Controller	Ether CAT Master RT
Press angle setting module	CEVV58S–00117
Analog signal input module	Ether CAT Box

To confirm the first method, the following steps were taken:

1. After analyzing the real production data, what high scrap leaves intolerable imprints in the part was determined and this height as the limit height $h_l$was considered;
2. Two eddy current sensors were installed in the stop blocks of the tool bottom plate in the opposite corners (see Fig. 2);
3. The eddy current sensors were calibrated so that they react only when the difference in the distances measured by them is greater than hl. It is important to avoid unnecessary stops in the stamping process;
4. Placed fragments of calibrated metal sheets of different thicknesses on the strip in various places of the tool and made strokes. For the experiment to be successful, the system needed to detect all fragments with a thickness greater than hl and not to react to thinner fragments;
5. Next, the system was tested using several fragments at once. In this way, it was checked if there could be a situation where scrap fell in several places of the strip, so the pressure was divided equally, and the system could not detect it;
6. Finally, the system under real conditions was tested. To speed up the experiment, the maximum allowable lubrication was used and the waste repellers from the punches were removed, which increased the probability that the waste would stick to the punch and therefore be lifted and fall onto the belt.

To find out if the second method is effective, the following steps were taken:

1. Two load sensors were installed in the press opposite corners (see Fig. 3);
2. By lowering the bottom plate in small steps, the press load variation curve was determined;
3. The breaking point of the curve was found;
4. The data acquired from the experiments were split into two parts - before and after the breakpoint;
5. A linear regression model was applied to each data group;
6. The results by comparing the values obtained before and after the suggested method implementation were analyzed.

3. Results of experimental research and their analysis

3.1. Results of experimental research and their analysis of the first method

The experiment was started with a nominal 4 mm thickness, S355MC material at 25 cycles per minute speed, using the level of lubrication specified in the tool's instruction manual and 50 parts produced at this rate. During the production, the readings of the sensors EC1 and EC2 were taken. Based on the obtained data, the signal curves of both sensors, presented in Fig. 5 and Fig. 6 were drawn, and how much the measured distance varies at each point was calculated. Both sensors EC1 and EC2 start to measure the distance from 128 to 252 degrees, making up an overall measurement length of 124 degrees. Measurement deviation from 128 to 162 degrees appears, because of the material strip deformation during the tool closing period. After evaluating the obtained results, a conclusion was made that the 'noise' of the sensor capture is 50 µm amplitude. Due to the noise, an inactive zone can mean that small foreign objects will be 'invisible' and the reliability of the system will decrease.

To determine an acceptable imprint depth, a calibrated thickness, 5x10 mm hardened steel (HRC – 65) plate on the strip was stuck, imitating scrap waste. After completing the full cycle with different thickness steel plates, the parts were assembled and inspected. The test was repeated several times with foreign material bodies of different thicknesses. The results of the research are shown in Fig. 7. A decision was made that imprints left by the 50 µm plate are acceptable, by the 100 µm plate are marginal, and by the 200 µm plate are not allowed.

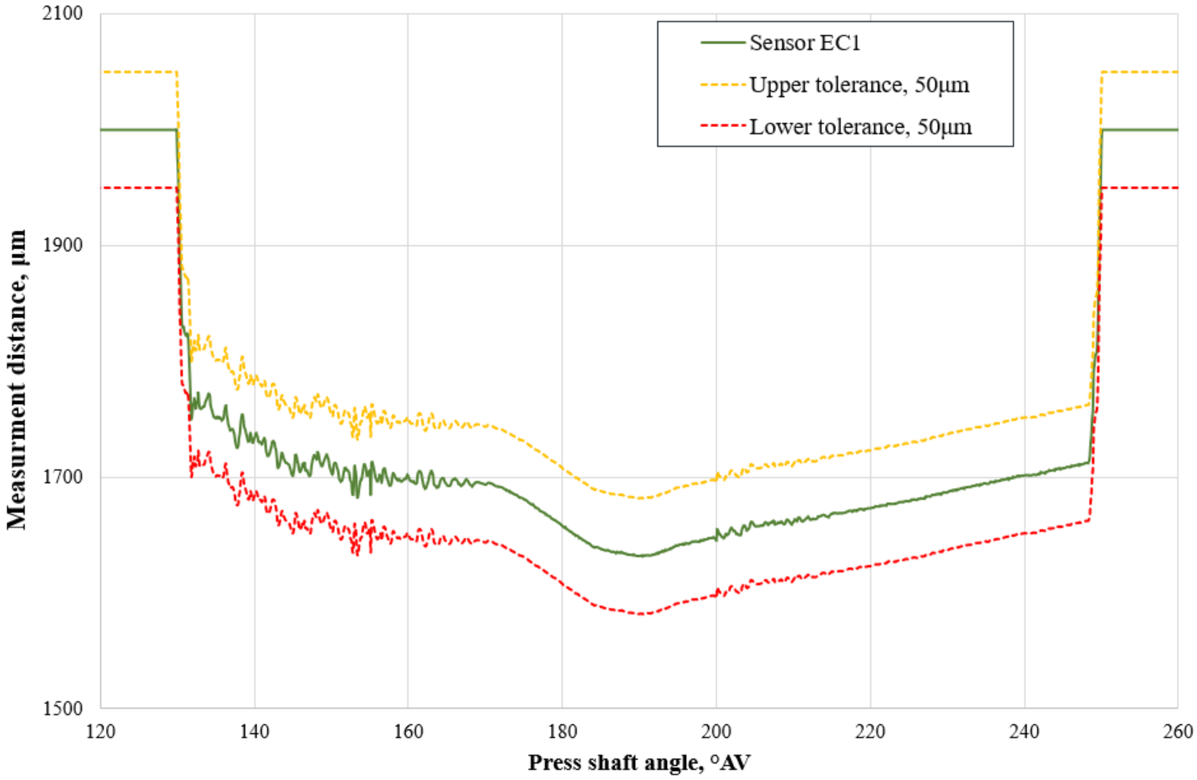

Fig. 5. Upper and lower limits of the sensor EC1.

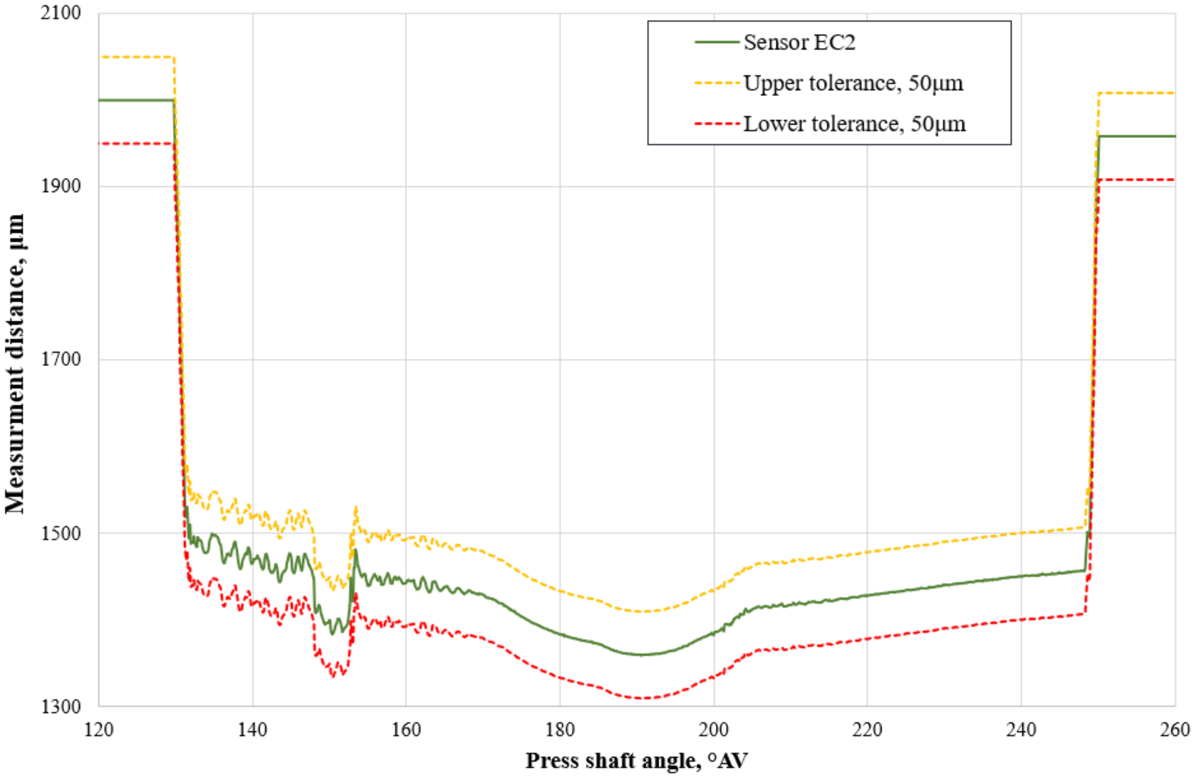

Fig. 6. Upper and lower limits of the sensor EC2.

In the automated mode, the sensors were not able to detect smaller scrap waste than 0.3 mm, even when the sensor's median was lower than the foreign body thickness. This could be explained by the tested material thickness itself (thick material compensates scrap thickness by deformation) and the design of the tool (comparatively, scrap plate thickness to stripper plate dimensions). The decision to experiment to examine the production stability with implemented sensors was made.

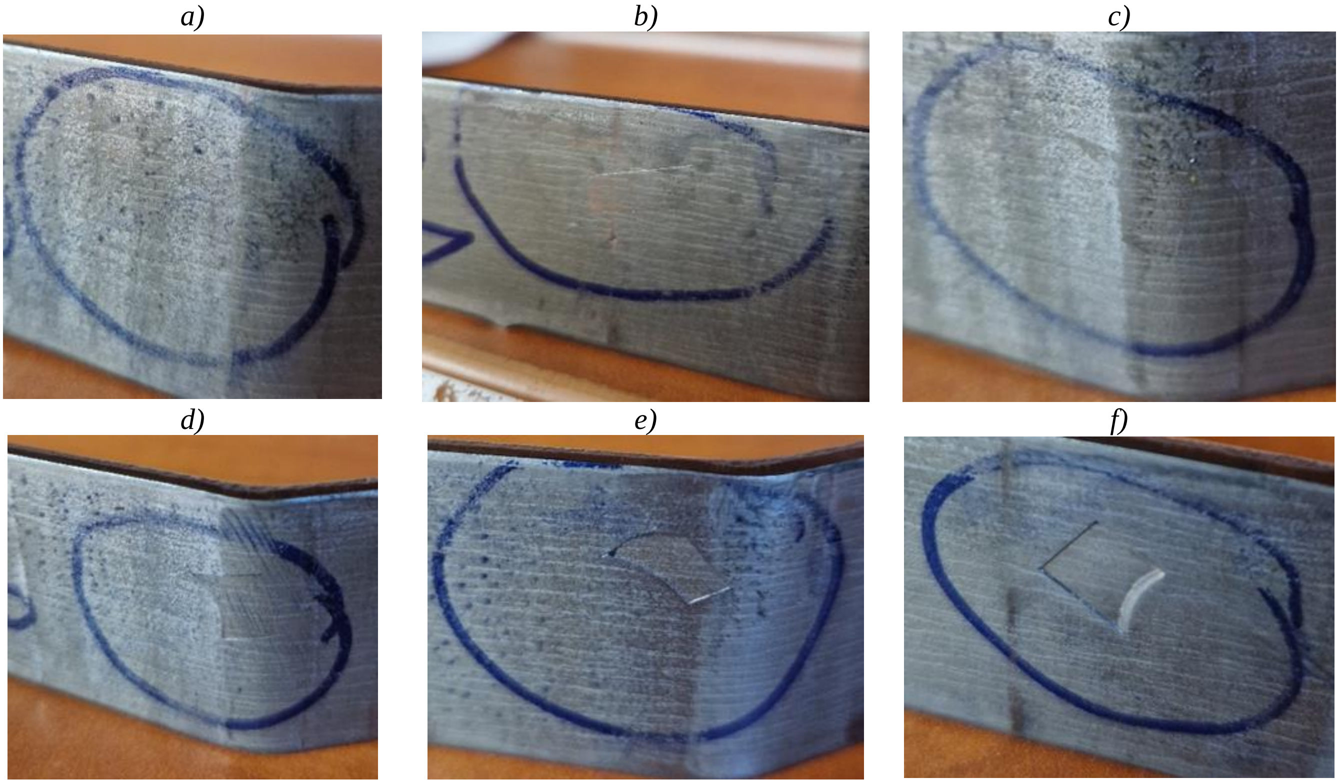

Fig. 7. Imprints on the part caused by the steel plate of different thickness: a) - 50 μm; b) - 100 μm; c) - 150 μm; d) - 200 μm; e) - 300 μm; f) - 400 μm.

The press was left to work in automatic - serial mode, 25 cycles per minute speed, and all process stops were recorded. Their summary is presented in Table 5.

Table 5. Serial production mode test results.

Case No.	*Time*	*Description*
1	08:15	Start
2	08:21	Stoppage due to part quality
3	08:43	Stoppage due to part quality
4	08:58	Stoppage due to part quality
5	09:25	Stoppage due to manually added 0,4 mm scrap plate and sensors EC1 and EC2 detection
6	09:45	Manual press stoppage by the operator
7	10:06	Stoppage due to part quality
8	10:25	Stoppage due to manually added 0,3 mm scrap plate which sensors EC1 and EC2 did not notice
9	10:35	Stoppage due to manually added 0,4 mm scrap plate and sensors EC1 and EC2 detection
10	10:39	Manual press stoppage by the operator
11	10:51	Stoppage due to manually added 0,4 mm scrap plate and sensors EC1 and EC2 detection
12	11:10	Stoppage due to manually added 0,4 mm scrap plate and sensors EC1 and EC2 detection
13	11:35	Stoppage due to manually added 0,3 mm scrap plate which sensors EC1 and EC2 did not notice
14	12:40	Stoppage due to manually added 0,4 mm scrap plate and sensors EC1 and EC2 detection
15	12:53	Manual press stoppage by the operator
16	13:00	End of production

As shown in the log, few unplanned stops occurred in the first hour, but that is not unusual in early production and stalls occurred unrelated to the sensors being tested. The scrap detection curve is shown in Fig. 8. Delay in stopping the press after the upper tolerance limit was exceeded appears due to the hydraulic system response time and press flywheel inertial force and takes 16 degrees to fully stop. Measurement deviation till 170 degrees appears, because of the material strip deformation during the tool closing period.

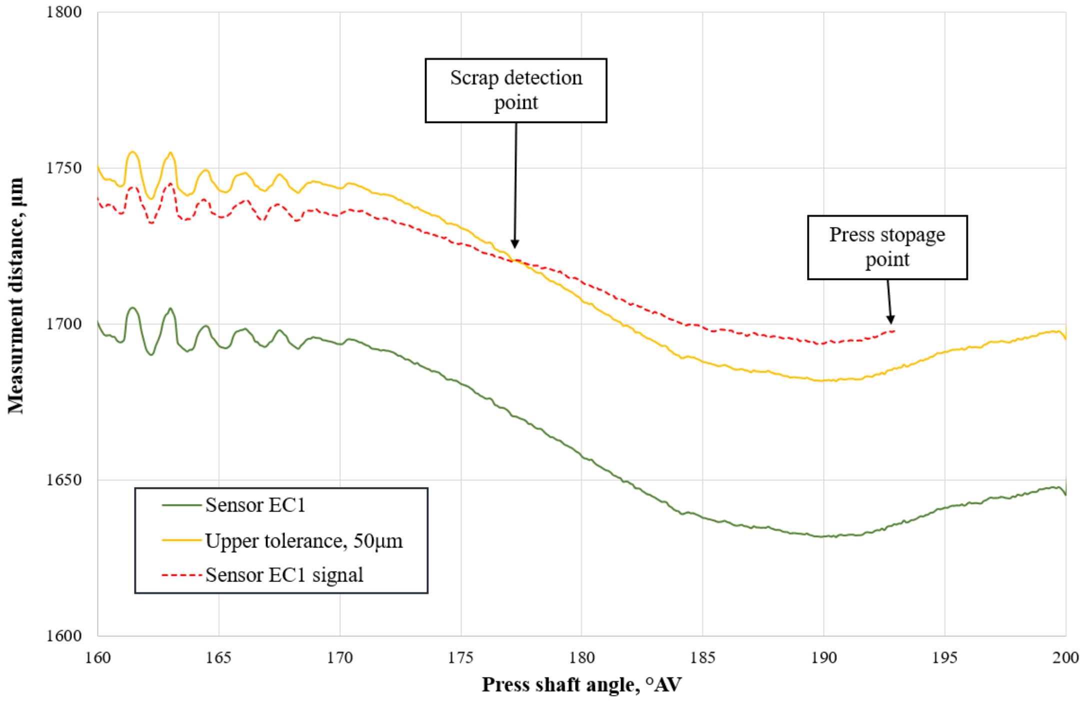

Fig. 8. 0.4 mm thickness scrap detection by the EC1 sensor.

Scrap plates were stuck to the oiled coil and carried deep into the tool. The sensors EC1 and EC2 immediately ordered to stop the process, so the protection worked properly. Later, 0.3 mm plates on the coil were stuck. In this case, the sensors did not stop the process, although they were not supposed to as determined in the earlier test. The test lasted around 5 hours and none of the production stalls occurred related to the sensors.

Summarizing the conducted research, a statement was made that the eddy current sensors can be used to detect foreign material bodies on the strip. Unfortunately, the desired 0.1 mm thickness foreign material body could not be detected. It is believed that the detectable thickness of foreign material bodies has a direct link with tool design.

3.2. Results of experimental research and their analysis of the second method

To apply the second method, firstly, it was proved that there is a clear breaking point in the press load dependence curve. For this, stamping tests were performed. During the stamping, the press operated in an automatic mode, at a speed of 25 cycles per minute. During each cycle, the readings of the press load sensors JZT1 and JZT2 were recorded. The observation interval was limited to the 190-210° section, where the load was at its highest point. The result is shown in Fig. 9. As can be seen, the measured force value rises from 36.4 to 261.7 kN in a 1.2 mm slide difference. Figure 9 also shows the regression analysis equations of the experimental data in two cases where the press slide is set from 380.3 to 381.1 and from 381.2 to 381.5 mm.

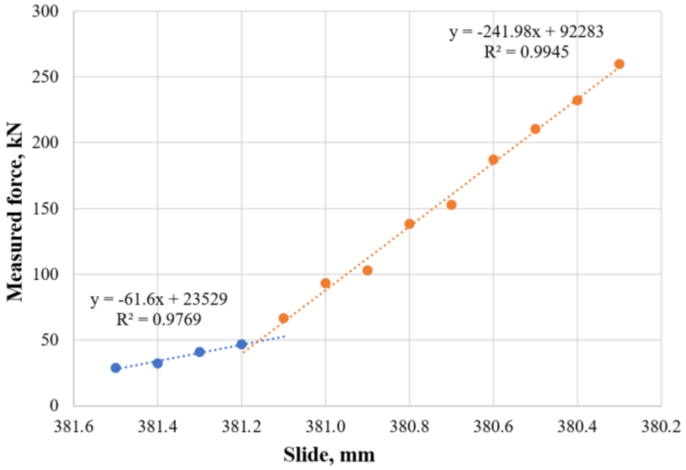

Fig. 9. Dependence between the measured load and press slide.

In both cases, the coefficient of determination was over 0.97%, indicating that both sets of data can be reasonably approximated by two separate lines that cross each other to form a V shape. According to them, following the procedure described above, it can be calculated that the ideal press slide for the experimental tool is as follows:

$$x = \frac{\alpha_2 - \alpha_1}{\beta_1 - \beta_2}, \qquad (2)$$

where x is calculated bottom tool position; α and β is line parameters.

The collected data from the first test are summarized and graphically presented in Table 6 and Fig. 10. The measured force value starts to climb to peak from 381.3 mm slide value.

Table 6. Dependence between the measured load and press slide, first test results.

Stripper position, mm	*Stroke No. 1, kN*	*Stroke No. 2, kN*	*Stroke No. 3, kN*	*Average force, kN*
380.4	161.5	162.5	161.8	161.9
380.5	143.6	143.7	143.1	143.5
380.6	119.6	119.4	119.6	119.5
380.7	103.9	103.9	103.9	103.9
380.8	86.4	86.3	86.4	86.4
380.9	68.4	69	68.6	68.7
381	55.6	55.8	55.6	55.7
381.1	39.2	39.4	39.5	39.4
381.2	29.9	29.9	29.9	29.9
381.3	22.1	22.1	22.5	22.2
381.4	13.5	14.2	13.5	13.7
381.5	10.6	11.4	11.1	11
381.6	9.1	9.5	9.6	9.4
381.7	2.7	2.5	2.5	2.6
381.8	3.6	4	4.6	4.1
381.9	2.7	2.3	2.7	2.6
382	2.7	2.9	2.7	2.8
382.1	3.8	3.3	4.1	3.7

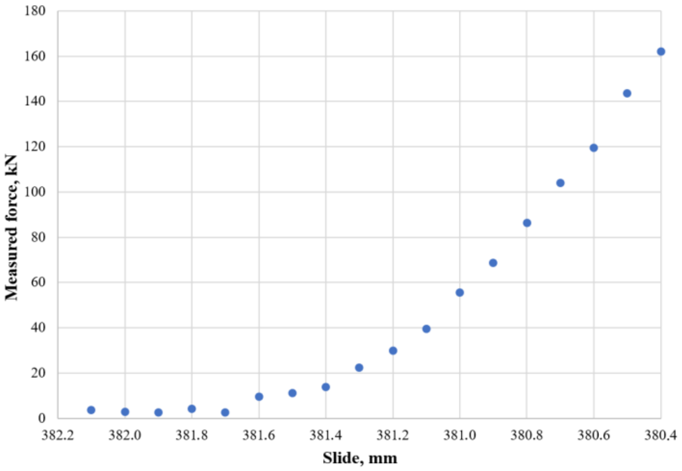

Fig. 10. Dependence between the measured load and press slide – first test.

No clear breaking point in the curve was observed in the results collected in the first test. It is most likely that the breaking point could not be seen because the determined and actual bottom position of the press does not match. It was assumed that the press measuring stroke variation occurred inaccurately or with an error. Therefore, it was decided to repeat the test for the second time: only this time an eddy current sensor was included, which measured the actual position of the stripper. The results are presented in Fig. 11. The measured force value starts to climb to peak from the 814 µm slide value.

The results showed that the proposed method for determining the optimal stroke length works best by using the part of the press load curve corresponding to high compression and following the measured rather than the determined position of the stripper. By using the second formula, the calculated slide in which the tool reached the bottom position was 381.16 mm. The tool bottom position set by the operator was 381.30 mm.

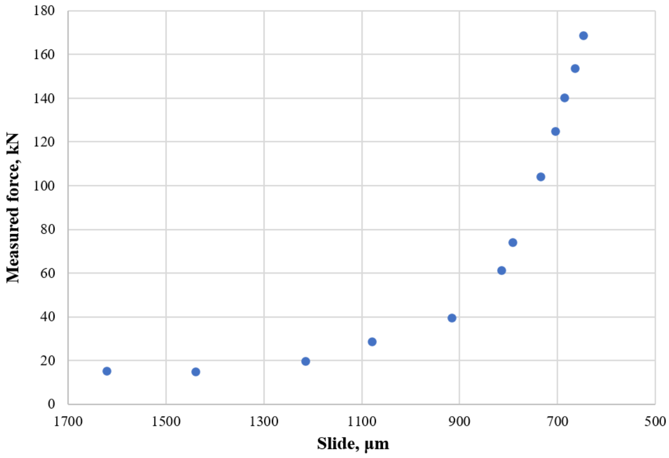

Fig. 11. Dependence between the measured load and press slide – second test.

In progressive stamping, due to production batch sizes exceeding 10.000 – 15.000 pcs., the overall process stability is very important. The process stability is evaluated by a separate characteristic's capability analysis. The capability analysis is a set of calculations used to assess whether a process is statistically able to meet a set of drawing requirements. The capability results were acquired by measuring parts with a Coordinate Measurement machine (CMM) and the results were processed with the Minitab Statistical software (Version 21.1.0). Two sets of data of one's produced part hole position (j0.5) were taken before and after implementing the proposed method in the existing tool. The position is dimensionless size and could be calculated using the following formula (3):

$$Position = 2 \cdot (dx^2 + dy^2)^{\frac{1}{2}}, \qquad (3)$$

where *dx* is the deviation between the measured *x* coordinate and the theoretical *x* coordinate; *dy* is the deviation between the measured *y* coordinate and the theoretical *y* coordinate.

Capability histograms of the process before and after implementing the method are presented in Fig. 12. USL shows the granted upper tolerance limit. Both sets of data are distributed according to the Normal distribution, but, after the method implementation, a clear peak is seen at the limit of 0.32. Before the method implementation, the data was distributed more evenly around the peak at the limit of 0.2. This indicated that, after the method implementation, the measurement value is expected to be higher but overall variation should be in the smaller limit.

In individual and moving charts (Fig. 13, 14) *UCL* means Upper Control Limit and *LCL* means Lower Control Limit. Both *UCL* and *LCL* values could be greater than the maximum or minimum value of the measured parameter which can be attributed to natural fluctuations and sampling size. *X* and *MR* indicate average measurement value. Both individual value and moving range are measured by millimeters between the quantity of controlled parts.

As seen from the Individual Value chart, after the method implementation, the Upper Control Limit increased from 0.3511 to 0.3806 as well and the average value increased from 0.2082 to 0.3046. It indicates that the new proposed method, the bottom position has an impact on the part dimensions.

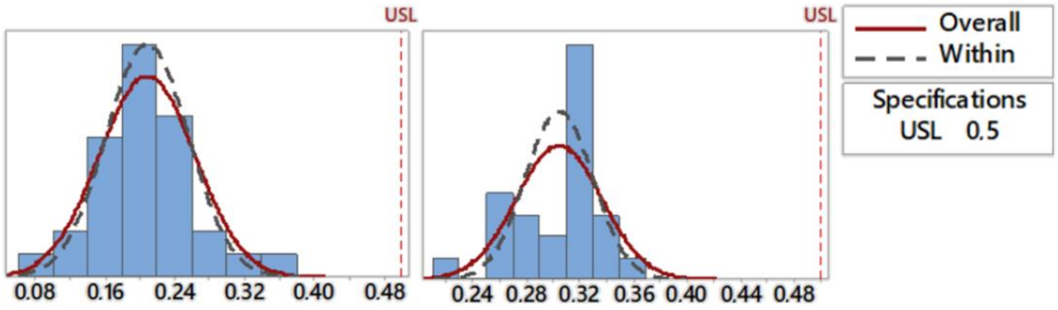
a) *b)*

Fig. 12. Capability histograms of the process: a) before the method implementation; b) after the method implementation.

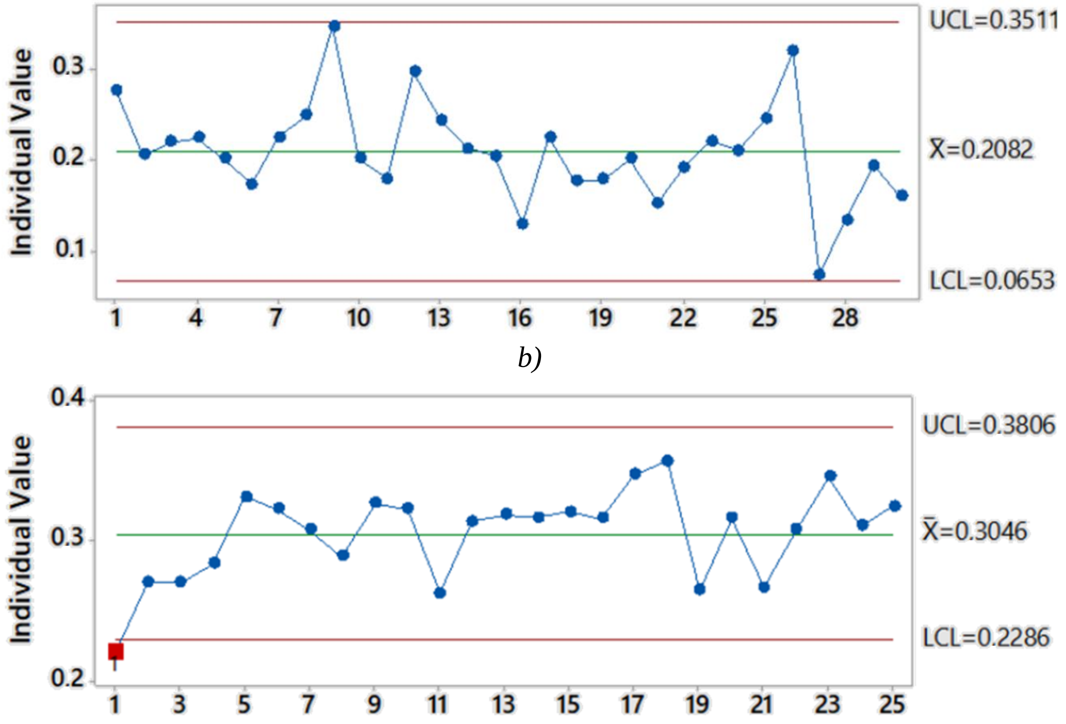
a)
b)

Fig. 13. Individual values chart of the process: a) before the method implementation; b) after the method implementation.

Looking only at the Histograms and Individual Value chart it may seem that the new proposed method has worsened the characteristics and the operator has achieved better part quality, but, if in consideration adding the Moving Range chart, this opinion will change.

A moving range measures how the variation changes over time when the data are collected as individual measurements rather than in subgroups [31]. As seen from the Moving Range chart after the method implementation the Upper Control Limit decreased from 0.1755 to 0.0934 as well and the average value decreased from 0.0537 to 0.0286. It indicates that the new proposed method could guarantee a more stable process along with tighter deviation zones.

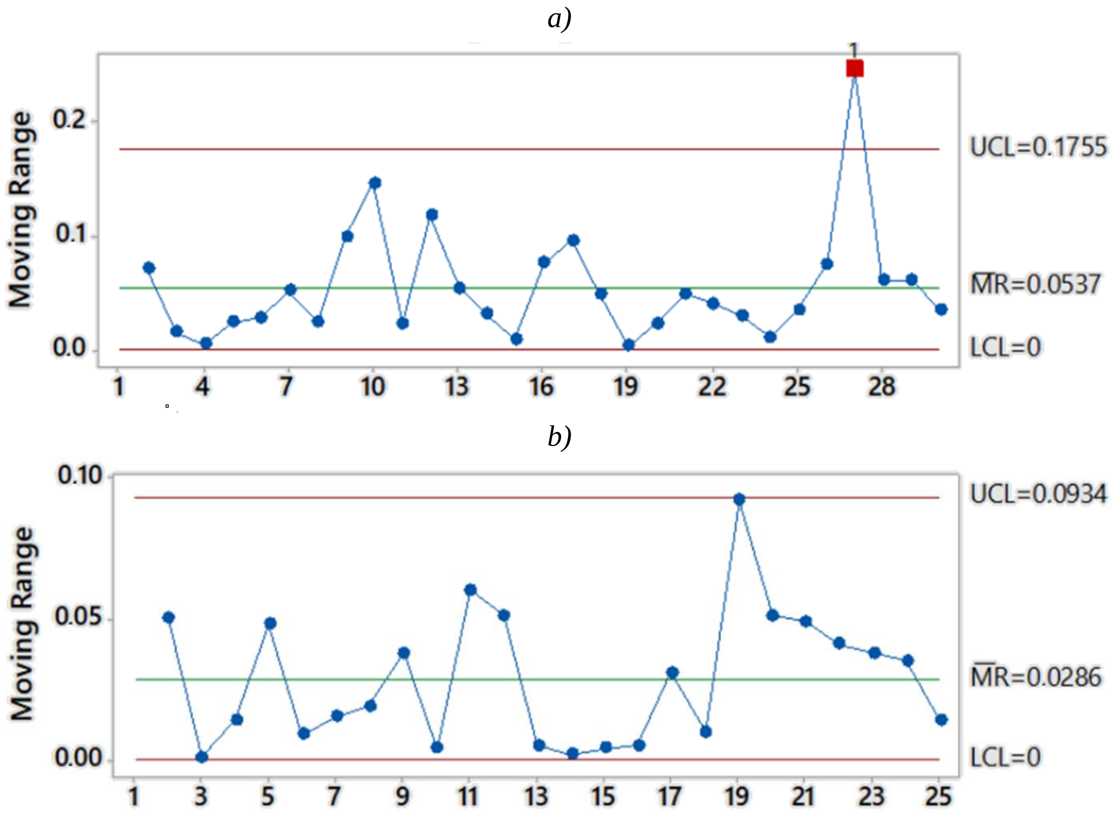

Fig. 14. Moving range chart of process: a) before the method implementation; b) after the method implementation.

The overall standard deviation (σ) of the part hole position measurement has decreased from 0.05519 (at 381.30 mm press slide) to 0.03184 (at 381.16 mm press slide). A standard deviation measure of how dispersed the data is in relation to the mean. Low, or small, standard deviation indicates that the data are clustered tightly around the mean [28]. The problem parts per million (PPM) indicator decreased from 0.06 (60.000 pcs. per million) to 0.00 (0 pcs. per million). And the Process Capability Index (Cpk) increased from 2.04 to 2.57. The Process Capability Index measures how close you are to your target and how consistent you are around your average performance [28]. According to the IATF standard, all characteristics should exceed Cpk of 1.33.

Summarizing the conducted research, a statement was made that the press load sensors can be used to determine the stroke length of the tool. For this, a several-step method was proposed and its application was demonstrated. Unfortunately, the obtained results showed that in this particular case, the press load curve break was not as obvious as expected. The curve break could only be reliably determined when using the load data when the strip is overpressed, which causes the risk of breaking the tool.

4. Conclusion

In this paper, two methods were suggested. Before implementing these two methods, a targeted review of the literature was performed, covering the problems of hydraulic systems, use of sensors, selection of suitable sensors, and stamping process development possibilities. Referring to the suggested methods of implementation, experiments and tests were planned, and suitable equipment was selected. The first method suggested that foreign material bodies could be detected by eddy current sensors because foreign bodies appeared may have no noticeable impact on press-used tonnage. The second method suggested that press load sensors could be used to determine the tool bottom position because the tool bottom position is most often determined by the operator and his visual experience.

After conducting the first method of experimental study and results analysis, the following conclusions are formulated:

1. 0.4 mm scrap body detection was achieved with implemented eddy current sensors, which is only 10% of the used material thickness;
2. The implementation of the eddy current sensors demonstrated a low frequency of unplanned triggers (stoppages) during the experiment.

After conducting the second method of experimental study and results analysis, the following conclusions are formulated:

1. Press load sensors were used to determine the stroke length of the tool. The calculated absolute tool bottom position value was 381.16 mm. The absolute tool bottom position value set up by the operator was 381.30 mm;
2. The difference between the calculated tool bottom position and the one set by the operator was 0.14 mm;
3. The determined tool bottom position increases the Process Capability Index (Cpk) from 2.04 to 2.57 indicating a more stable production process;
4. Statistically, after the method implementation, the measurement value is expected to be higher but the overall variation should be in smaller limits;
5. Based on the acquired results of both methods, implementing the in–die sensors was considered successful and applicable to new tools.

The study demonstrated possible extension of eddy current and load sensors usage. Further work will aim to select and optimize sensorsensor structures in the design stage for industrial applications. The subject of the research will be the development of algorithms to optimize the location of sensors, and quantity and detect possible high-risk areas in progressive stamping tools.

Acknowledgments

The results of this paper were achieved in cooperation within the UAB “Stansefabrikken Automotive” and VILNIUS TECH – Vilnius Gediminas Technical University.

References

1. Zhang C, Liang C, Yu D, Zhang C, Xiao H and Wang H. Application MEMS multi–sensors for monitoring the forming load of the stamping press. IEEE International Conference on Mechatronics and Automation 2012; 1518–1523, doi:10.1109/ICMA.2012.6284362.
2. Jian C, Ekkard B, Mingwang F, Gao R, Liang B, Merklein M, Schmidt M, Yanagimoto J. Manufacturing of advanced smart tooling for metal forming. CIRP Annals 2019; 68(2): 605–628, https://doi.org/10.1016/j.cirp.2019.05.001.
3. Ravindran D, Yu–Chih S. Sensors for Sheet Metal Forming, Sheet Metal Forming: Processes and Applications, Edited By Altan T, Tekkaya A. ASM International 2012; 301–315, https://doi.org/10.31399/asm.tb.smfpa.t53500301.
4. Asensi P, Montes I, García N. In Process Measurement Techniques Based on Available Sensors in the Stamping Machines for the Automotive Industry. In Key Engineering Materials. Transport Technical Publications, Ltd 2022; 926: 853–861, https://doi.org/10.4028/p–gvqkd4.
5. Balluff. Metal forming application note, http://www.clarkandosborne.com/resources/pdf/MetalFormingApplications.pdf.
6. Kaman. Inductive technology handbook, https://www.kaman.com/sites/default/files/Kaman_Applications_Handbook_WEB%20%281%29.pdf.
7. Dickerson G. Demystifying die protection. Sensors and controls: eyes and brain of die protection. Stamping Journal 2010. November/December: 12 –13 p.
8. Bachmanm K. Sensors clear the way for high–speed stamping. Stamping Journal 2008, https://www.thefabricator.com/stampingjournal/article/stamping/sensors–clear–the–way–for–high–speed–stamping.
9. Bird D. Where sensors make sense. Stamping Journal 2008, https://www.thefabricator.com/stampingjournal/article/stamping/where–sensors–make–sense.

10. Hedrick A. Die Science: Die protection techniques. Stamping Journal 2017, https://www.thefabricator.com/stampingjournal/article/stamping/die–protection–techniques.
11. Bird D. Electronic sensors augment error–proofing, quality control programs. The Tube & Pipe Journal 2013, https://www.thefabricator.com/tubepipejournal/article/testingmeasuring/electronic–sensors–augment–error–proofing–quality–control–programs.
12. Lynch T. Metal Stamping Sensors Boost Efficiency, Quality. 2015, http://www.kenmode.com/blog/metal–stamping–sensors–boost–efficiency–quality.
13. Puchalski A, Komorska I. Generative modelling of vibration signals in machine maintenance. Eksploatacja i Niezawodność – Maintenance and Reliability 2023; 25(4), https://doi.org/10.17531/ein/173488.
14. Overly S. Recovering from press overload: Protection systems help to sense overload and minimize machine, tool damage. Stamping Journal 2001, https://www.thefabricator.com/thefabricator/article/stamping/recovering–from–press–overload–protection–systems–help–to–sense–overload–and–minimize–machine–tool–damage.
15. Bury P, Stosiak M, Urbanowicz K, Kodura A, Kubrak M, Malesińska A. A Case Study of Open- and Closed-Loop Control of Hydrostatic Transmission with Proportional Valve Start-Up Process. Energies 2022; 15(5), https://doi.org/10.3390/en15051860.
16. Deptuła A, Stosiak M, Cieślicki R, Karpenko M, Urbanowicz K, Skačkauskas P, Małgorzata A. Application of the Methodology of Multi-Valued Logic Trees with Weighting Factors in the Optimization of a Proportional Valve. Axioms 2023; 12(1), https://doi.org/10.3390/axioms12010008.
17. Groche P, Hohmann J, and Übelacker D. Overview and comparison of different sensor positions and measuring methods for the process force measurement in stamping operations. Measurement 2019; 135: 122–130, https://doi.org/10.1016/j.measurement.2018.11.058.
18. Li X, Bassiuny A. Transient dynamical analysis of strain signals in sheet metal stamping processes. International Journal of Machine Tools and Manufacture 2008; 48(5): 576–588, https://doi.org/10.1016/j.ijmachtools.2007.06.010.
19. Garcia E, Montés N, Llopis J, Lacasa A. Miniterm, a Novel Virtual Sensor for Predictive Maintenance for the Industry 4.0 Era. Sensors 2022; 22(16): 6222, https://doi.org/10.3390/s22166222.
20. Peinado–Asensi I, Montés N, García E. Virtual Sensor of Gravity Centres for Real–Time Condition Monitoring of an Industrial Stamping Press in the Automotive Industry. Sensors 2023; 23(14): 6569, https://doi.org/10.3390/s23146569.
21. Zhou C, Liu K, Zhang X, Zhang W and Shi J. An Automatic Process Monitoring Method Using Recurrence Plot in Progressive Stamping Processes. IEEE Transactions on Automation Science and Engineering 2016; 13(2): 1102–1111, doi:10.1109/TASE.2015.2468058.
22. Jin J. Individual Station Monitoring Using Press Tonnage Sensors for Multiple Operation Stamping Processes. Journal of Manufacturing Science and Engineering 2004; 126(1): 83–90, https://doi.org/10.1115/1.1643749.
23. SK–Reporter. Combined force and acoustic sensors safeguard stamping processes, 2014. https://www.impaxptg.com/pdf/baumann–stamping–reporter–article.pdf.
24. Karabacak Y. Deep learning–based CNC milling tool wear stage estimation with multi–signal analysis. Eksploatacja i Niezawodność – Maintenance and Reliability 2023; 25(3), https://doi.org/10.17531/ein/168082.
25. Garcia C. Artificial intelligence applied to automatic supervision, diagnosis and control in sheet metal stamping processes. Journal of Materials Processing Technology 2005; 164: 1351–1357, https://doi.org/10.1016/j.jmatprotec.2005.02.031.
26. Kozłowski E, Antosz K, Mazurkiewicz D, Sęp J, Żabiński T. Integrating advanced measurement and signal processing for reliability decision–making. Eksploatacja i Niezawodność – Maintenance and Reliability 2021; 23(4): 777–87, https://doi.org/10.17531/ein.2021.4.20.

27. Duan R, He J, Feng T, Huang S, Chen L. Effective sensor placement based on a VIKOR method considering common cause failure in the presence of epistemic uncertainty. Eksploatacja i Niezawodność – Maintenance and Reliability 2021; 23(2): 253–62, https://doi.org/10.17531/ein.2021.2.5.
28. Azamirad G, Arezoo B. Structural design of stamping die components using bi–directional evolutionary structural optimization method. International Journal of Advanced Manufacturing Technologies 2016; 87: 969–979, https://doi.org/10.1007/s00170–016–8344–7.
29. Finnerty J. 50 Tips for Better Die Protection. 2019, https://www.slideshare.net/Wintriss/50–tips–for–better–die–protection.
30. Niemietz P, Kornely M, Trauth D, et al. Relating wear stages in sheet metal forming based on short– and long–term force signal variations. Journal of Intelligent Manufacturing 2022; 33: 2143–2155, https://doi.org/10.1007/s10845–022–01979–0.
31. Geometric Dimensioning and Tolerancing. The Ultimate GD&T Guide. ASME Y14.5–2009. Press: 2009.