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# The concept of automatic generation of hydraulic press cycle

DENIS JANKOVIČ, ROK NOVAK, MARKO ŠIMIC & NIKO HERAKOVIČ

**Abstract** The development of smart hydraulic press that allows rapid adaptation to high-volume variant production is a major challenge. Besides tool management, setting the control parameters, which can be considered as a correct press cycle, is an important part to achieve agile production. This paper presents a new approach to automatically generate a hydraulic press cycle where the important data of the production plan is known, such as the data or setting of the forming tool and the data of the product. In this case, RFID tracking system is used to read the tool/product data, which is input data for the mathematical algorithm for calculating the characteristic points of the hydraulic press cycle. The characteristic points are sent to the local PLC and stored as a matrix. The Beckhoff TwinCat platform is used for process control. Finally, a simple bending process is shown as a use case for concept verification.

**Keywords:** • hydraulic press • forming tool • RFID • automatic-generation • press cycle •

CORRESPONDENCE ADDRESS: Denis Jankovič, University of Ljubljana, Faculty of mechanical engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, denis.jankovic@fs.uni-lj.si. Rok Novak, University of Ljubljana, Faculty of mechanical engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, rok.novak@outlook.com. Marko Šimic, University of Ljubljana, Faculty of mechanical engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, marko.simic@fs.uni-lj.si. Niko Herakovič, University of Ljubljana, Faculty of mechanical engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, niko.herakovic@fs.uni-lj.si.

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## 1 Introduction

The progressive digitalization and interconnectivity of machines and equipment, improve production processes through automation and self-optimization. Intelligent and smart manufacturing systems in smart factories provide optimization of work plan, higher productivity, increase in Overall Equipment Efficiency (OEE) and reduction in manufacturing costs [1]. Hydraulic systems are not yet at the level of smart manufacturing systems, so expert systems with integrated smart sensors and actuators need to be developed to provide the necessary smart data flow. Standardized communication between subsystems and interoperability must be achieved to allow the expert system to make functional improvements and extensions [2]. Condition monitoring is required to fully understand the operational characteristics of the hydraulic system so that the stability of the hydraulic system and processes can be confirmed and automatic control optimization and predictive maintenance can be determined if necessary [3]. Complex hydraulic components such as hydraulic valves are already considered as a separate unit which has its own intelligent software and tools for data analysis and are able to draw the right conclusions about the component's operability [4]. Intelligent algorithms can introduce artificial intelligence (AI) into hydraulic systems and components to provide them with the ability to self-predict, self-adapt and make decisions instead of human operators [5]. Adaptive control systems for setting the control parameters considered as a correct hydraulic press cycle during the desired planned forming process can be designed based on mathematical [6, 7, 8] or numerical models [9]. Proper tool selection [10] and optimized tool change scheduling [11] result in higher OEE, higher productivity, reduced cycle times, and better dimensional tolerance of the product. However, demanding customer requirements increase product variability, which is associated with the constant modification and optimization of the production schedule. Therefore, it is necessary to increase the flexibility of the hydraulic press by using expert systems that allow adaptation to the changes.

# 2 The concept of smart hydraulic press

## 2.1 Expert system

According to the guidelines of I 4.0, the expert system of smart hydraulic press is proposed as its intelligence. The hydraulic press is treated as an individual intelligent system that can be integrated with the Manufacturing Execution System (MES) and Enterprise Resource Planning system (ERP) of the Smart factory. Figure 1 shows the concept of the hydraulic expert system with the inputs, outputs, Overall Equipment Efficiency sub-module (OEE) that consists of visualisation and statistical data analysis, acquisition of important process parameters and local intelligence.

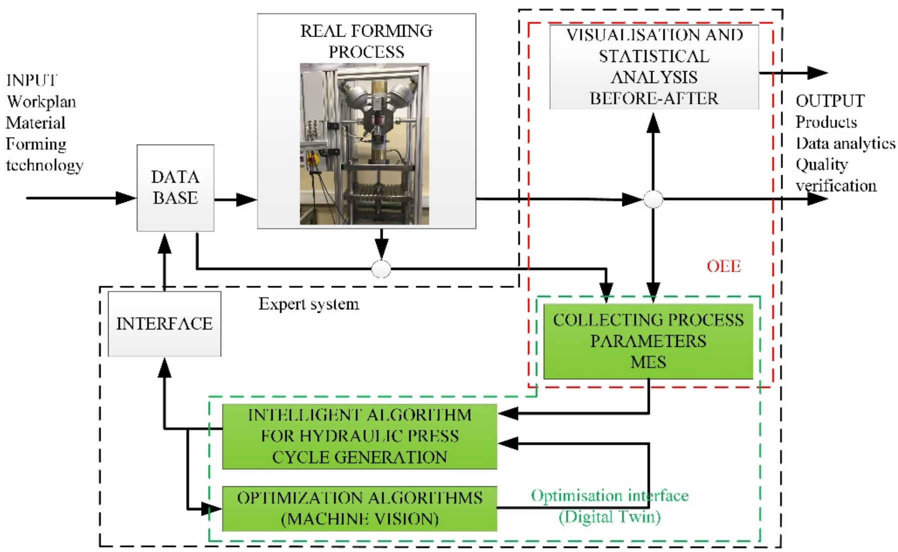


**Figure 1: The concept of hydraulic expert system.**

The main part of the paper presents the intelligent algorithm for the automatic generation of the hydraulic press cycle based on the data stored in the local database module (collecting process parameters MES). The important input data mainly includes the workplan, material properties and technology parameters. The workplan provides crucial parameters regarding the type and the number of products to be manufactured. The material specifies the products in detail, i.e. the geometry properties (important in terms of handling, positioning and forming process). The technology provides crucial parameters of the machine and all other tools used to manufacture the products. The proposed expert system consists of six important steps: 1) reading and gathering all the input parameters from ERP and MES, 2) storing the parameters in local database module, 3) validation of the current state of the hydraulic press, tooling, material and confirmation the "ready for produce" status, 4) definition of the proper forming process, tooling, material (specimens), 5) automatic generation of the hydraulic press cycle, 6) execution of the forming process, process and product quality analysis and optimization of the press cycle to achieve quality of products.

In step 1, the information and input data from various sources is forwarded to a local database. At the global level of the smart factory ERP and MES systems provide production plan requirements such as product type (length, width, height), material properties, required forming operation (bending, deep drawing, coining etc.), required die tool, process parameters (bending angle, deep drawing height etc.). Tooling geometry properties are gathered based on digital models from research and development and construction department. Material properties are determined using tensile and flexural test [12]. The parameters of the hydraulic systems are measured with sensors as described in chapter 2.2. The expert system compares the real and the reference process parameters and sends a request for parameter adjustment via the interface.

In step 2, the collected data is sorted and filtered so that the subsystems involved in a hydraulic system can access and use the smart data for further operations.
In step 3, the expert hydraulic system uses the data collected from the sensors and actuators to self-validate the state of the hydraulic system, the currently installed die tool as well as its setting and the condition of the individual components of the hydraulic system. The hydraulic expert system predicts the necessary events/activities that guide the machine operator through the HMI interface, or, in the case of automation, robots that perform the handling operations. The expert system ensures that the forming process requirements are met.

In step 4, the specimen dimensional properties and type of material are selected. Based on the material properties, the forming cycle (ram speed) is adjusted as needed in the forming phase. If necessary, instructions are given for changing the die tool. Based on the collected data and expert system confirmation the product parameters are determined, which are the input data for the intelligent algorithm. In step 5, the intelligent algorithm determines the characteristic points of the forming process and considers the tool geometry errors that occur during the ram movement and are described in more detail in Chapter 3.

During the forming operation the product quality is monitored with the machine vision system (step 6). The type of forming process needs to be considered, as each forming operation has different impacts on the product quality. Springback effect is ever present in the case of sheet metal bending, where the sheet metal tries to revert back into its straight form, once it is bent [6], [8]. In the case of deep drawing the product quality can be measured with the process parameters such as forming force and blanking force to prevent fracture and wrinkling on products [9].
Optimization algorithms in step 6 monitor the product quality and process parameters and in case of bad product quality make decisions to improve the product quality.

## 2.2 IoT concept of hydraulic press

The proposed IoT of a hydraulic press represents an intelligent network of subsystems interconnected in a closed communication loop, as shown in Figure 2. Therefore, the presented IoT structure is divided into three subsystems: (1) database or local cloud, (2) expert system, and (3) control system. The designed IoT concept of hydraulic press enables rapid data exchange between devices so that the devices can perform operations without time delay. The responsiveness of the system is increased, which improves the efficiency of the production plan. When unpredicTable events occur, decision-making algorithms are used to improve system functionality at the edge device. Understanding the edge computing in the concept of smart factory, the hydraulic systems or its components have the potential to be implemented as an individual smart sub-system. The first subsystem of the IoT concept for hydraulic press is (1) the local cloud of processed data. Here, the historical data is available to all devices that have permission to read the data. The proposed local cloud stores the data such as the workpiece storage state, tool warehouse state, die tool properties and other data relevant to the process monitoring. To determine the condition of the hydraulic system several sensors can be used:

- Position sensor to determine the cylinder displacement and hydraulic valve spool displacement.
- Strain gauges to determine frame deformation.
- Pressure sensors to monitor pressure in hydraulic cylinder.
- Force sensor to monitor the force generated, i.e., the forming force.
- Electrical current sensors in combination with electrical control voltage measurement to calculate the energy consumption.
- Tachometer to measure the speed of the electric motor.
- RFID systems to track input material and die tool changes settings.
- Inductive sensors or microswitches to monitor the die tool set-up.
- Machine vision systems to monitor the specimen position and quality of the products.

The purpose of (2) expert system is to perform the self-adjustment and optimization mechanism of hydraulic system based on current system status and provide a better-quality product with an improvement loop as described in depth in chapter 2.1.

The hydraulic press cycle and the control signal for servo valve is thereby corrected by closed-loop control analysing the difference between the reference signal and the error predicted by the expert system. The control system (3) reduces the error and correct the servo valve control signal to achieve better performance.

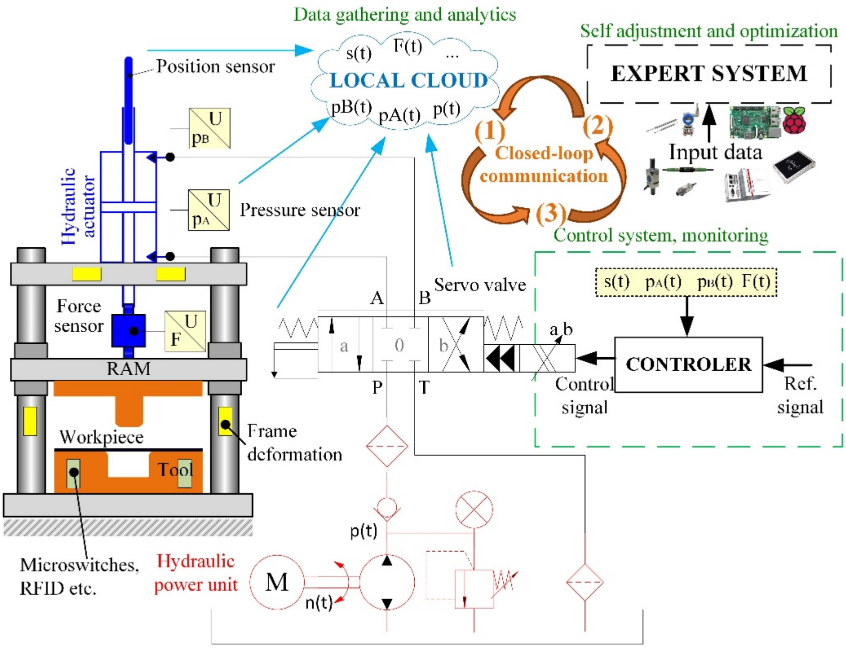


**Figure 2: Scheme of hydraulic press divided into several functional IoT sub-systems.**

## 3 Hydraulic press cycle generation – main structure of the intelligent algorithm

The structure of the proposed algorithm for automatic generation of the hydraulic press cycle consists of three basic elements, as shown in Figure 3. The first element presents the input data such as order requirements, hydraulic press characteristics, product shape and die tool geometry. Based on the variability of the product shape and the order requirements the self-recognizing part of the algorithm defines variables such as the bending angle and the required tool for the bending process. The purpose of the second element is to automatically generate the hydraulic press cycle considering the input data. The algorithm is the most important part and is represented in chapter 3.2 in detail. The output data of the proposed algorithm represents the hydraulic press cycle given by characteristic points of the forming cycle. The characteristic points are forwarded to the controller in the form of a reference signal to perform closed-loop position control.

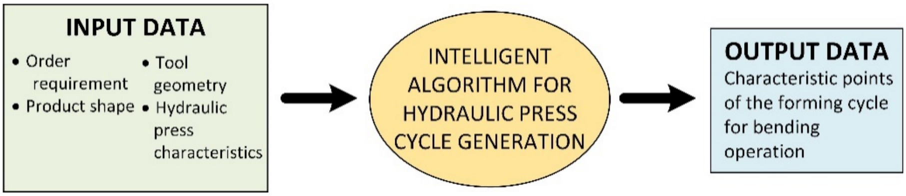


**Figure 3: Structure of intelligent algorithm for hydraulic press cycle generation.**

## 3.1 Intelligent algorithm for hydraulic press cycle generation

Various forming processes require different forming cycles that define a different number of characteristic points. For our case, we propose the hydraulic press cycle characterized by 7 typical points, as shown in Figure 4. Such a cycle is suiTable for bending process, deep drawing, etc. Each point is characterized by position of the cylinder/ram and the time (s, t).

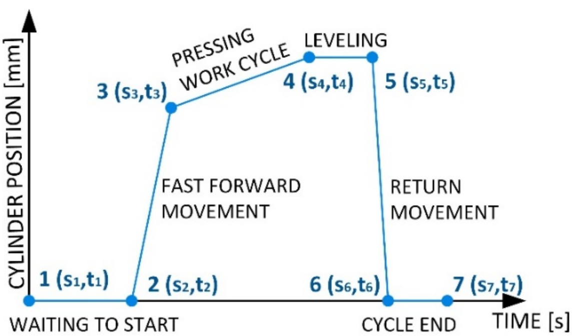


**Figure 4: Hydraulic press cycle given by characteristic points.**

Points (1) and (2) define the waiting phase of the forming cycle. The positions $s_1$ and $s_2$ are defined by considering the characteristics of the hydraulic press (stroke range) and the ram movement required for the handling process. The characteristics can be gathered from digital models of the press construction and the die tool and specimen properties. The time period between $t_1$ and $t_2$ is used to satisfy the forming conditions and to position the specimens correctly.

The fast forward movement of the ram towards the specimen is characterized by points (2) and (3). The maximal permissible cylinder velocity is determined by position $s_3$ and time $t_3$. Point (3) represents the starting point of the pressing work cycle and is chosen to allow a few mm of free movement before upper die tool touches the specimen. In our case we chose 3 mm of free movement for presented hydraulic press and bending process. The most important point of the hydraulic press cycle represents point 4 ($s_4$, $t_4$). The forming process demands appropriate ram speed to achieve proper deformation of the specimen, which is adjusTable by changing the time $t_4$. A more detailed calculation of the proper movement of the ram ($s_4 = x_{p,true}$) for the bending process is described in chapter 3.3. The time $t_5$ of levelling phase, between points (4) and (5), is optional and depends on the forming process requirements. The return movement is characterized by points (5) and (6) where $s_6 = s_2 = s_1$. Time $t_6$ is defined in similar way as for fast forward movement to achieve maximal permissible speed of hydraulic cylinder. During the time between points (6) and (7), the cycle ends and allows the setting of the waiting period $t_7$, while $s_7 = s_6 = s_2 = s_1$.

### 3.2 Determination of hydraulic press cycle (point 4)

The primary function of the intelligent algorithm is to determine the characteristic point 4 ($s_4$, $t_4$) just before a tool touches the specimen of the forming cycle shown in Figure 4. The secondary function of the algorithm is to determine the error during the sheet metal bending cycle caused by the movement of the sheet metal on the contact point of the tool. The main parameters describing the geometrical characteristics of the specimen and the die tool are shown in Figure 5. Here *L* represents the distance between the two supports of the lower die tool, *R* the lower die tool radius, *r* the upper die tool radius, and d the sheet metal thickness.

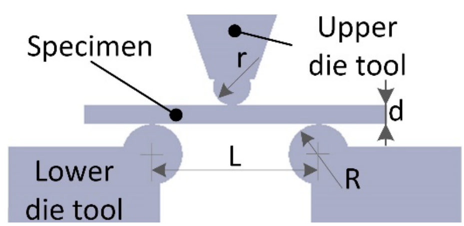


**Figure 5: Dimensional properties of forming tool.**

Figure 5 shows an initial contact point between a die tool and a specimen. The final movement of the ram is defined by the desired bending angle $\alpha$ (Figure 6). Equation (1) represents a simplified calculation of the forming depth $x_p$, without taking into consideration the error caused by the sliding motion of the specimen on the supports.

$$x_{p,simpl} = \frac{L}{2 \cdot tan\frac{\alpha}{2}} \tag{1}$$

However two types of errors needs to be taken into consideration and added to the forming depth $x_{p,simpl}$ given in simplified equation (1). The first type of error occurs due to specimen slippage (from contact point 1 to contact point 2) on the lower die tool due to the assumed geometric properties of the lower die tool as shown in Figure 49. The contact point between specimen and the lower die tool is determined by the radius of the lower tool support $R$ and the bending angle $\alpha$.

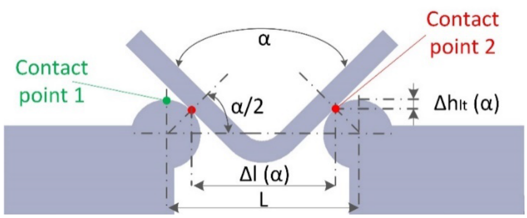


**Figure 6: Error due to lower die tool.**

Thus, the equation for the actual distance between contact points $\Delta l(\alpha)$ (between the specimen and the lower die tool) can be expressed by equation (2). Also, the actual height of the contact points $\Delta h_{lt}(\alpha)$ must be considered with equation (3) where bending angle $\alpha$ is considered.

$$\Delta l(\alpha) = L - 2R \cdot cos\frac{\alpha}{2} \tag{2}$$

$$\Delta h_{lt}(\alpha) = \left(1 - sin\frac{\alpha}{2}\right) \cdot R \tag{3}$$

The second type of error occurs due to the assumed geometric properties of the lower die tool $\Delta h_{lt}(\alpha)$. It is given as the difference between the height $H$ and the radius of upper die tool $r$, as shown in Figure 7. The specimen thickness $d$ is also considered in the height error $\Delta h_{lt}(\alpha)$.

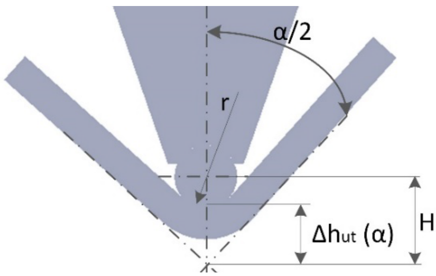


**Figure 7: Error due to upper die tool.**

The height $H$ is derived according to Pythagorean Theorem and expressed by equation (4). Here in equation (4) the error that occurs due to geometric properties of the upper die tool h is expressed as the difference between the sum of error $H$ and the radius of the tool $r$. As shown in equation (5) the error $\Delta h_{ut}(\alpha)$ is due to the radius of the upper die tool $r$ and the variable bending angle $\alpha$.

$$H = \frac{r+d}{sin\frac{\alpha}{2}} \tag{4}$$

$$\Delta h_{ut}\ (\alpha) = H - r = \frac{r+d}{sin\frac{\alpha}{2}} - r \tag{5}$$

Since both types of errors caused by the lower die tool $\Delta l(\alpha)$, $\Delta h_{lt}(\alpha)$ and the upper die tool $\Delta h_{ut}(\alpha)$ are not considered in the simplified equation (1), equation (6) represents a true forming depth, where the variability of the bending angle $\alpha$ (product requirement variability) and die tool geometry are considered.

$$x_{p,true} = \frac{l(\alpha)}{2\cdot tan\frac{\alpha}{2}} - \Delta h_{lt}(\alpha) + \Delta h_{ut}(\alpha) \tag{6}$$

## 4 Integration of algorithm in real hydraulic press

The interoperability between emerging connected devices and the speed of communication determines the efficiency of the expert system. Radio Frequency Technology (RFID) is used to read the word order via RFID tags. An intelligent algorithm processes the input data and generates a characteristic point for the bending operation. In the next step, the Graphical User Interface (GUI) is used to monitor and control the manufacturing process.

### 4.1 RFID material tracking and forming tool set-up recognition

The use of RFID in production systems is becoming increasingly popular for exchanging data between edge systems in a smart factory, such as a hydraulic system [13]. RFID technology can be used to collect important data about the forming die tool installed in the hydraulic press. Here, the identification code (ID) for each die tool stored in a warehouse and for each pallet containing samples is written on an RFID tag, as shown in Figure 8.

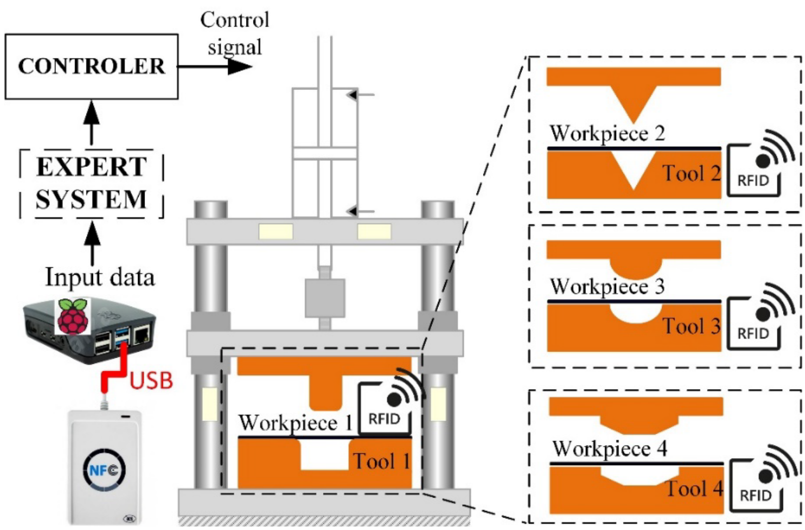


**Figure 8: Concept of die tool and input material recognition.**

The installation instructions are prepared by an expert system. In the proposed concept of hydraulic press, the microcontroller Raspberry Pie is used as an edge device for die tool tracking, material tracking and production plan determination using RFID tag. The RFID reader is connected to the microcontroller using USB communication protocol. The intelligent algorithm can perform automatic die tool recognition, die tool set-up recognition, and input material recognition (specimens) based on the currently manufactured product. The expert system with the algorithm also verifies the correctness of the input material, the selected or installed tool, the setup of the die tool, and the characteristics of the hydraulic press that allows the planed forming process to be performed. In the event of an error, the request is sent to the HMI interface to replace or correctly install the currently installed die tool or replace the input material.

## 4.2 Graphical user interface and hydraulic press cycle

The Graphical User Interface (GUI) shown in Figure 9 is designed to visualize the measured parameters of the hydraulic press and guide the operator until the production plan is completed. In case of unaccepTable errors during the production process, warnings are displayed on the GUI, such as excessive system pressure, incorrectly installed die tool, open safety door and product remaining in the die tool.

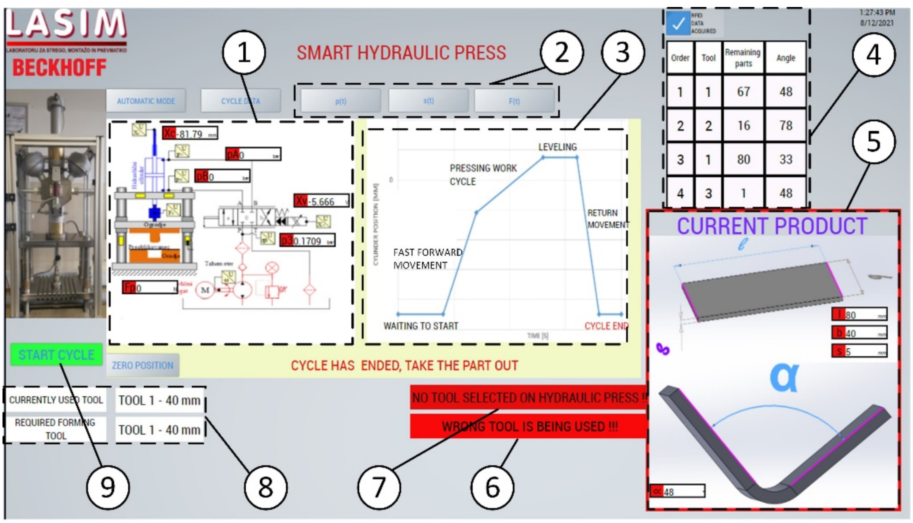


**Figure 9: Graphical user interface for hydraulic press.**

The developed GUI consists of the nine key elements that enable press cycle operate the press and manage the manufacturing process: 1) real-time monitoring of important parameters, 2) monitoring of pressure *p(t)*, ram stroke *s(t)* and force *F(t)*, 3) monitoring of the forming cycle and determination of the current forming phase, 4) production plan and important planning data, 5) current product being manufactured and its characteristics, 6) warning signs in case the wrong die tool is used, 7) warning signs in case the tool is not properly set, 8) message to the operator when the forming process is finished, and 9) button to start the forming cycle.

The successful calculation of the hydraulic press cycle (the characteristic points) for the given product is shown in Figure 10. The characteristics points of hydraulic press cycle are defined based on local database information's (characteristics of hydraulic press, die tool and current product). The stroke of the ram (point 4, $x_{p,true}$) to achieve the proper forming angle of the product is calculated automatically according to the procedure presented in chapter 3.3, while the times are gathered from the local base satisfying the overall cycle time.

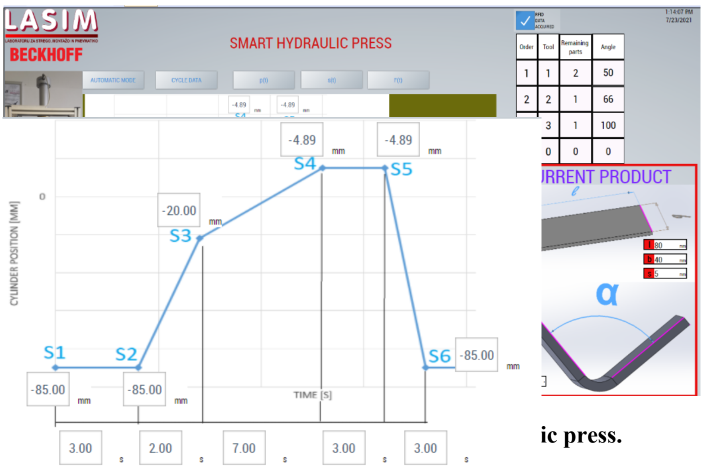


**Figure 10: The characteristics points of hydraulic press cycle.**

## 5 Conclusions

The paper focuses on the concept of smart hydraulic press suiTable for integration in smart factory. One of the proposed solutions consists of an expert system and an integrated intelligent algorithm for the automatic generation of the hydraulic press cycle. The other concept is an IoT solution that includes the hydraulic press, the die tool, the input material, the local cloud database, the expert system, and the control system. RFID technology is used to detect the input material and the die tool. In our solution, the bending process is considered as a demonstration application for validating the intelligent algorithm for automatic generation of the hydraulic press cycle. The newly proposed approach and algorithm considers the characteristics of the hydraulic press such as the cylinder stroke range, the geometrical and dimensional parameters of the hydraulic press, the die tool and the specimen characteristics and dimensions. Based on these characteristics stored in the local database, the intelligent algorithm uses the data to automatically calculate the characteristic points of the hydraulic press cycle. The proposed solution represents the first step towards an intelligent and flexible hydraulic press capable of adopting to different production plans.

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**References**

[1] Wang B., Tao, Tai, F., Fang, X., Liu, C., Liu, Y., Freiheit, T. (2021). Smart Manufacturing and Intelligent Manufacturing: A Comparative Review. Engineering, vol. 7, no. 6, pp. 738–757, 2021, doi: 10.1016/j.eng.2020.07.017

[2] Haack, S., Meißelbach, A. Industrial Hydraulics. (2018), Are we really on track concerning Industry 4.0 ?. *11th Int. Fluid Power Conf.* 11. IFK, March 19-21, Ger., 2018.

[3] S. S. Chawathe. (2019) Condition monitoring of hydraulic systems by classifying sensor data streams. *IEEE 9th Annu. Comput. Commun. Work. Conf. CCWC 2019*, pp. 898–904, 2019, doi: 10.1109/CCWC.2019.8666564.

[4] Xu, B., Shen J., Liu, S., Su, Q., Zhang, J. (2020) Research and Development of Electro-hydraulic Control Valves Oriented to Industry 4.0. A Review. Chinese J. Mech. Eng. English Ed., vol. 33, no. 1, doi: 10.1186/s10033-020-00446-2

[5] Stadnicka, D., Litwin, P., Antonelli, D. (2019). Human factor in intelligent manufacturing systems - Knowledge acquisition and motivation. *Procedia CIRP*, vol. 79, pp. 718–723, 2019, doi: 10.1016/j.procir.2019.02.023.

[6] Zhang, Z., Ma, R., Wang, C., Zhao J. (2019) Research on Springback Control in Stretch Bending Based on Iterative Compensation Method. Math. Probl. Eng., vol. 2019, doi: 10.1155/2019/2025717.

[7] Ma R., Wang C., Zhai R., Zhao, J. (2019). An Iterative Compensation Algorithm for Springback Control in Plane Deformation and Its Application. *Chinese Journal of Mechanical Engineering (English Edition)*, vol. 32, no. 1. 2019, doi: 10.1186/s10033-019-0339-5.

[8] Osman. M., Shazly. M., Mokadddem, A. El., Wifi, A. S. (2010) Springback prediction in V-die bending: modelling and experimentation. *J. Achiev. Mater. Manuf. Eng.*, vol. 38, no. 2, pp. 179–186

[9] Meng, B., Wan, M., Wu, X., Yuan, S., Xu, X., Liu, J. (2014). Development of sheet metal active-pressurized hydrodynamic deep drawing system and its applications. *International Journal of Mechanical Sciences*, vol. 79. pp. 143–151, 2014, doi:10.1016/j.ijmecsci.2013.12.005.

[10] Kumar, S., Singh, R. (2005). An intelligent system for selection of die-set of metal stamping press tool. *J. Mater. Process. Technol.*, vol. 164–165, pp. 1395–1401, doi: 10.1016/j.jmatprotec.2005.02.066.

[11] Opritescu, D., Hartmann, C., Riedl ,W., Ritter, M., Volk, W. (2019). Low-risk bypassing of machine failure scenarios in automotive industry press shops by releasing overall capacity of the production networks. *J. Manuf. Syst.*, vol. 52, no. June, pp. 121–130, 2019, doi: 10.1016/j.jmsy.2019.05.007.

[12] Kim, H.,Gu, J. C., Zoller, L. Zoller. Control of the servo-press in stamping considering the variation of the incoming material properties. *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 651, no. 1, 2019, doi: 10.1088/1757-899X/651/1/012062.

[13] Centea, D., Singh, I., Boer, J., Boer. RFID in Manufacturing: An Implementation Case in the SEPT Learning Factory. *Procedia Manuf.*, vol. 51, no. 2019, pp. 543–548, 2020, doi: 10.1016/j.promfg.2020.10.076.