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Development of a flexible tooling system for sheet metal bending

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ABSTRACT

This article presents the design and development of a flexible tooling system for sheet metal bending. The flexible tooling system aims to reduce manufacturing disturbances and increase the efficiency of the forming process. First and foremost, the structural behaviour of the sheet metal is investigated using the finite element method for the numerical simulation of the three-point bending process. The analysis' findings enabled the prediction of component reaction to loads, which are essential for the further optimization and enhancement of the tooling system's flexibility. At the initial stage of the development phase, SolidWorks, the computer-aided design software, is utilized to visualise the flexible tooling system and improve the tooling connectivity design. Furthermore, the prototype is developed by integrating mechanical and electrical components, such as the Arduino Mega microcontroller, stepper motors, and digital stepper drivers. Automation is achieved by programming the Arduino microcontroller board and controlling the stepper motors' movement to ensure precise displacement and speed control of the forming tools. The tooling system's major qualities are its high flexibility, achieved through the implementation of two moveable support cylinders and the possibility of being further upgraded to a closed-loop forming system. The higher level of automation and optimization of the sheet metal bending process can lead to improved processing efficiency and help achieve the desired formed products with higher quality and the required geometric tolerance. It is expected that the development of a flexible tooling system will find widespread application in sheet metal bending processes, resulting in reduced material costs, rapid equipment set-up and higher processing repeatability.

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1. Introduction

Sheet metal forming processes are manufacturing processes used to deform the sheet metal plastically into desired shapes. Sheet metal forming is widely used as a mass production processing technology due to its high processing speed and low processing cost compared to other methods [1]. Metal forming processes are an important field of research since the modern industry constantly aims for advanced processing performance and product quality control [2]. For minimizing production costs and achieving desired product quality, the determination of optimal process parameters, such as tool and workpiece geometrical data, material properties, contact conditions, and other technological parameters is of critical importance [3, 4]. Complicated physical phenomena, such as tool elastic deformations, sheet metal's material non-linearities, springback occurrence caused by material elastic recovery, and dynamic friction situations, impact output product quality [5]. Better output results can be obtained by studying the relative performance of a material in a given application and considering all the influential parameters that occur throughout the forming process. The parameters of the process, including acting stresses, strains, and temperature fields, as well as local conditions of the microstructure (e.g., damage, grain size, structural composition) and the surface (e.g., lubricant layer thickness, surface micro-geometry), are used to describe the process and its limits [6]. Finite element simulation is essential for evaluating the material response to different influential parameters, further reducing forming process uncertainties and eliminating any deviations of the finished part from the initial design [7]. Optimizing all the process parameters and controlling the process limits can be extremely challenging, though it can improve the performance of the forming process used for the manufacturing of parts with a more accurate final geometry. Applying methods for modelling, simulation and optimization of production processes leads to the generation of new and better manufacturing solutions and to the optimization of process parameters [8].

Industries have developed various advanced technologies that can contribute to the creation of autonomous operational systems and process enhancements [9]. Effective implementation of Industry 4.0 technologies [10] offers more efficient and higher-quality production processes, as well as enabling predictive and preventative maintenance, resulting in reduced downtime and decreased long-term operational costs. The advanced connectivity of the embedded systems allows collecting and exchanging real-time information to identify, locate, track, monitor, and optimize the production processes [11, 12]. This allows for improved product quality, efficiency, and flexibility in producing customized items on a wide scale while reducing resource consumption [13, 14]. Sensors that monitor the part during the manufacturing process, actuators with sufficient flexibility and adaptability to allow modifications in response to changing process conditions, and model development with sufficient speed and efficiency to allow operation under changing process conditions are just a few of the features that can be implemented to improve the sheet metal forming processes [15]. Fig. 1 shows a closed-loop concept of metal forming control system that uses multiple sensors to monitor and optimize the metal forming process.

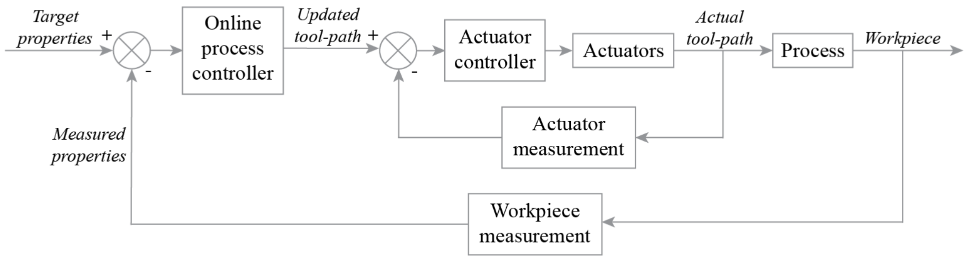


Fig. 1 A system diagram for closed-loop control of sheet metal forming process [15]

1.1 Fundamentals of sheet metal bending process

The production of high-precision sheet metal components is extremely important in the automotive, electronics, and housing-utensil industries [16]. The stability of the forming process is affected by a variety of structural properties, process disturbances, and complex parameter correlations. Therefore, manufacturers must constantly evaluate their strategies and search for new methods to improve process efficiency and achieve the desired product quality. One of the most frequent forming processes used in the manufacturing of sheet metal components is bending [17]. In sheet metal bending, plastic deformation occurs when the specimen undergoes permanent deformation or a non-reversible change in shape in response to applied loads. The formability of sheet metals, which refers to the material's capability to undergo plastic deformation to a specific shape while meeting quality requirements, is primarily influenced by the general mechanical properties, including the thickness and anisotropic features of the materials [18]. Dai *et al.* emphasize that during the design stage of the bending process, specific sheet material characteristics must be considered (i.e., Young's modulus, yield stress, the ratio of yield stress to ultimate tensile stress, initial anisotropy yielding criterion, and the microstructure of the material) [19]. FEM is the main technique for predicting sheet metal forming processes and determining the distribution of stresses and strains in the material, forming forces, and possible locations of defects in advance [20, 21]. For the successful application of the FEM to predict springback, it is necessary to know and understand the influence of numerical parameters on simulation results. In the metal forming process, the bending force has to be determined so that the sheet metal can undergo plastic deformation and the desired shape can be achieved. Nevertheless, after the forming force is released, the material partially returns to its original shape due to its elastic recovery, which is known as springback [22]. Springback is expressed as the difference in dimension between the fully loaded and the unloaded configuration [23]. As a result, the springback must be considered in the metal forming process, since it decreases the bent angle of the sheet metal by a few degrees. The springback significantly influences the dimensional accuracy of the bent sheet metal; therefore, controlling and minimizing this challenging phenomenon can improve the bending process's accuracy.

1.2 Optimization of sheet metal forming processes

The fourth industrial revolution influences sheet metal forming operations with modifications, including enhanced manufacturing productivity, increased product quality, decreased technological difficulties for adapting the equipment, and reduced processing time. By developing and integrating sensing technologies for the visualization and monitoring of the forming process, production control (e.g., quality verification and traceability of the parameters) can be enhanced [24]. The expansion of smart manufacturing is enabled by innovative technologies that improve the cyber-physical systems (CPS) for better communication, process control, decision-making, and problem-solving capabilities [25]. Medić *et al*. [26] investigated the contribution of advanced digital technologies offering the greatest benefits to the Industry 4.0 production, considering the real-time monitoring of manufacturing processes as one of the key elements. In smart manufacturing, the digital twin (DT) technique is utilized to simulate physical entities, predicting their performance and behaviour under various scenarios [27]. The digital twin establishes the mapping and interaction between the physical and digital worlds, delivering specific information and presenting all of the influencing factors, thereby providing comprehensive technical guarantee and optimization capabilities [28]. In the event of an unplanned change or shutdown, the digital twin simulates numerous possibilities and delivers the optimal solution in real-time, allowing the real system to be constantly improved through a feedback loop. In the simulated environment, the DT of a real manufacturing activity can show, evaluate, and improve the process. The digital twin allows for process parameter identification, monitoring, and prediction, as well as comparison of the digital equivalent of the process to its recorded parameters obtained from the measured data from the physical environment. The digital twin's decision-making abilities can enable modification of the formed part's geometry by timely responding to predictions of potential process uncertainties that may occur during the forming process and by controlling the forming tool actuators to react fast to the instructions. The accuracy of the forming process, the quality of the finished product, and the processing efficiency can continuously improve with the implementation of the digital twin.

Developing appropriate sensors for monitoring the material flow during the sheet metal forming processes is extremely challenging. Fig. 3 depicts an example of applicable technology using a contact-based material flow measurement sensor known as a rolling ball sensor [29]. The mechanical transmission of the sheet metal's plane movement onto the rolling ball serves as the foundation for this sensor. The rotating motion of the ball is transmitted to two perpendicularly positioned measuring rollers. Each measuring roller has a slotted running wheel that runs inside a photoelectric barrier and converts rotation to electrical impulses without contact. With this sensor technique, the material flow direction, velocity, and path may all be monitored independently in two orthogonal directions.

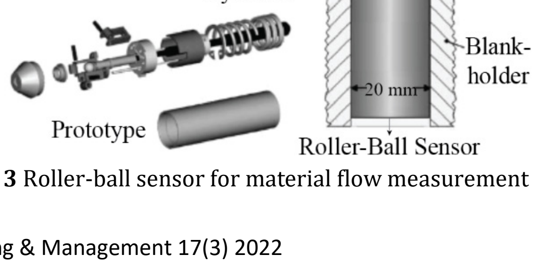


Fig. 3 Roller-ball sensor for material flow measurement [29]

Sah *et al*. [30] created a draw-in sensor based on the mutual inductance concept, as shown in Fig. 4. Current is stimulated in the first coil, causing electromotive force or induced voltages in the secondary coil. When metal is present close to the coils, the degree of mutual inductance varies; thus, the produced signal in the secondary coil reflects how much of the coil is covered up, providing a measure for the material draw-in amount. When monitoring the material draw-in of stamping processes, the contactless sensor eliminates the difficulties of conventional sensing. For example, when measuring material draw-in in stamping operations using standard sensing techniques, the edge wrinkle may cause loss of contact and difficulties in detecting the displacement.

Groche *et al*. [31] presented sensor fasteners that allow mechanical connections between the parts to be monitored for analysing forces and operational loads. To gather combined force and torque information in diverse regions, the sensor unit must be able to deliver and receive loads in all directions of space. The sensor fastener shown in Fig. 5 integrates a sensor component into an empty load-carrying model in the shape of a bolt. Simplified sensors are connected to the surface of the sensor body. To meet its functional requirements, the module incorporates an axial preload. A tensile load would otherwise cause the connected components to separate and interrupt the force transmission. In the sensor set-up, three strain gauges are placed on three sides of a rectangular cross-section. Individual axial forces and bending torques may be calculated by analysing each signal provided by the strain gauge. As a result, the novel concept enables a mechanical connection between the forming tools and the machine, as well as monitoring of operating loads.

Hinchy *et al*. [32] developed a physical manufacturing testbed that bends metal into V-brackets alongside a digital twin counterpart consisting of the three elements: machine, product, and process. Finite element modelling is utilized in the digital twin to forecast product outcomes and estimate product stress throughout the bending process. As shown in Fig. 6, the bending machine moves a V-press relative to a static V-die with a pair of high-torque stepper motors, while a load cell measures load throughout the bending process. An Internet of Things (IoT) [33] enabled microcontroller is used to control the system; it is capable of wirelessly transferring sensor data. A database of product attributes, such as material type, material qualities, product geometry, and product status, form the product's digital twin. The digital twin can be used to secure the expected results in metal forming operations, for example, the desired final bend angle. The digital twin concept contributes meaningfully to the metal forming process by predicting and optimizing the operation through the implementation of cyber-physical systems.

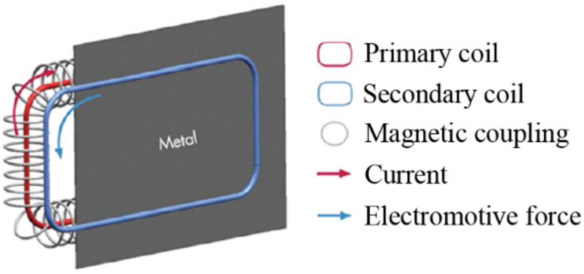


Fig. 4 Draw-in sensor based on the mutual inductance concept [30]

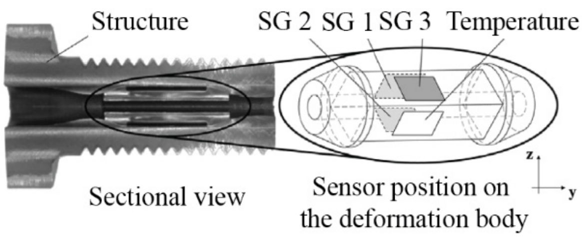


Fig. 5 Configuration of the sensor fastener [31]

Haag *et al*. [34] developed a digital twin concept for a bending beam test bench to prove that the digital representation of an individual product can play an integral role in a fully digitalized product life cycle. Fig. 7 presents the entire set-up of the digital twin system. The digital twin primarily includes the bending beam's precise computer-aided design (CAD). The following steps include a combination of finite element technique simulations to reflect the complete test bench accurately in a virtual environment. An architecture based on the message-queuing telemetry transport (MQTT) protocol links the physical and digital twins. As parameters, either the resulting force on the beam or the ultimate displacement of the beam is entered into the system. Furthermore, the parameters are sent to the broker, who sends them to the physical twin, which then goes to the predetermined position until the movement or force is obtained, and then checks the other variables. The variable is then returned to the broker, who passes it along to the digital twin and IoT network. The digital twin starts an automated FEM analysis with the real force or movement values. Via the broker, the estimated findings are also sent back to the IoT platform, where they may be evaluated to the physical outputs. The objective is to automatically produce the digital twin and establish the network connection with its physical twin to make the concept applicable to a wide variety of devices.

By analysing data from prior research work in sheet metal forming, the set of scientific concepts and technologies being recently employed to improve the forming processes' quality have been identified. This article proposes a novel perspective of increasing the flexibility of the three-point bending process by developing an innovative tooling system. The employment of two moveable support cylinders in addition to the forming punch that conducts the bending operation improves the configuration of the forming tools, resulting in higher efficiency and reduced forming time. The device is designed to provide greater opportunities for further optimization of the bending process and the capacity to be upgraded to a closed-loop forming system.

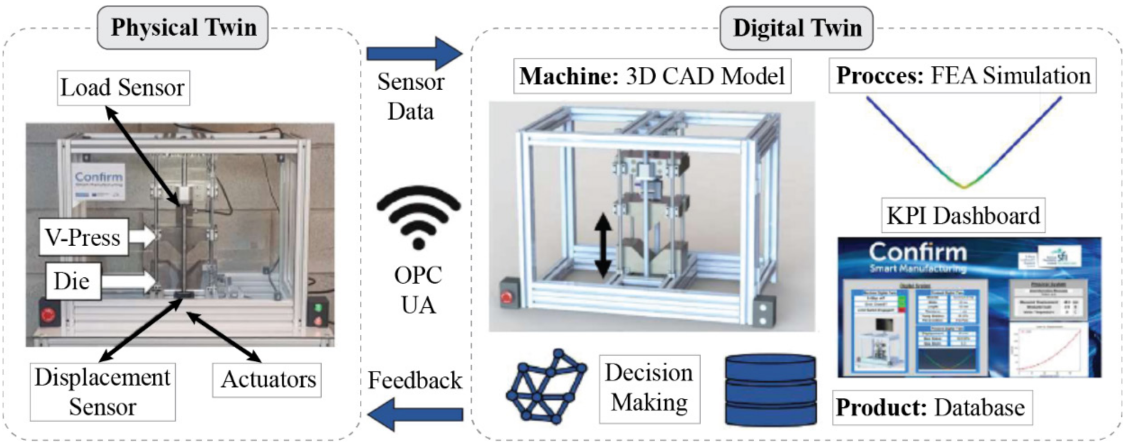


Fig. 6 Integration of physical and digital bending system [32]

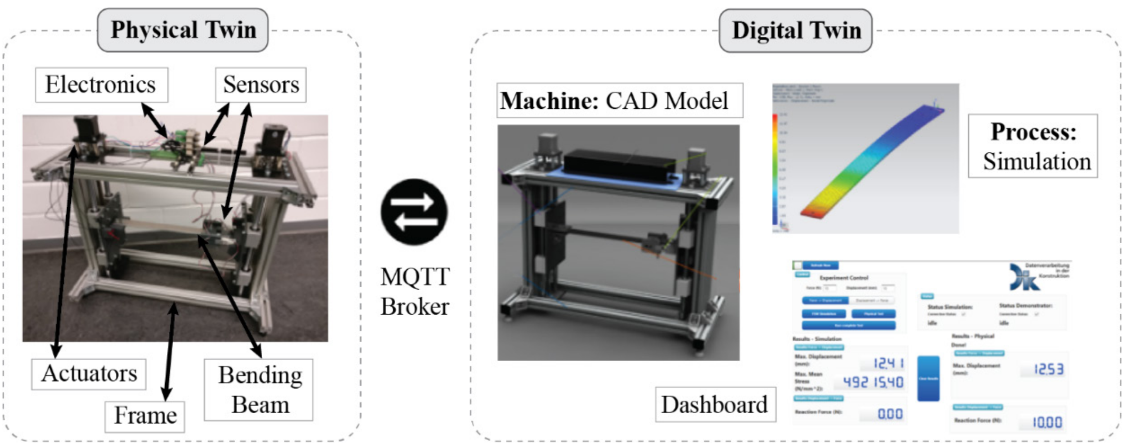


Fig. 7 Digital twin concept for bending beam test bench [34]

In the presented article, Section 1 reviewed the literature on topics relevant to the research undertaken, including introductory definitions related to the bending processes and the material properties of sheet metals. Also, the impact of Industry 4.0 on sheet metal forming operations, as well as several techniques for improving forming processes, were discussed. Furthermore, Section 2 describes the implemented methods using finite element analysis and computer-aided design for the visualization of the flexible tooling system. Section 3 presents the obtained results from the numerical simulations and the developed prototype of the flexible tooling system for sheet metal bending. Section 4 reviews the major findings in this article and offers recommendations for further research related to this study.

2. Materials and methods

This section describes the flexible tooling system set-up in detail, as well as the methods utilized to obtain the desired results. Fig. 8 illustrates the set-up of the three-point bending system and the overbending technique used in this investigation. The direction of the arrows indicates the movement of the forming tools that perform the sheet metal bending process. The three moveable forming tools exert force on the sheet metal, causing it to bend until the desired final shape is achieved. The overbending technique is used to obtain the desired bent angle by angularly bending the sheet metal over the specified angle and achieving the chosen final shape after the occurrence of springback.

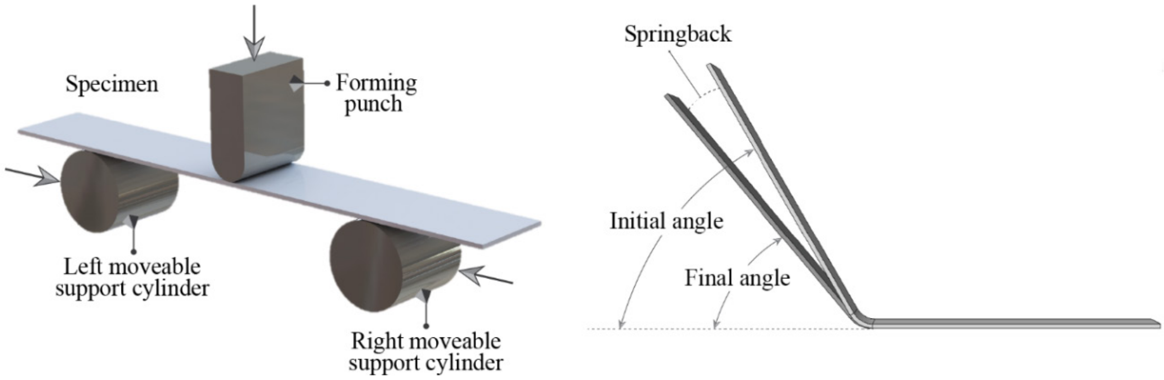


Fig. 8 Set-up of the three-point bending system and springback phenomenon

2.1 Finite element analysis

In the performed study, the initial findings of the three-point bending tests with flexible supports are obtained with a numerical simulation using the finite element software Abaqus. The goal of the numerical simulations was to determine the optimal process parameters for achieving a 90° bent angle of the specimen after springback. The model consists of sheet metal, forming punch and two support cylinders with precisely defined dimensions. The material properties, the design of the forming tool, the processing conditions and the tool wear are factors that influence the quality of the product, and their prediction is of great importance [35]. The thickness and material type of the sheet metal, as well as the radius of the forming tools, were the main parameters considered in the simulation. The sheet metal has a length of 140 mm, a width of 20 mm, and a thickness of 1 mm. The forming punch has a radius of 5 mm, while the moveable support cylinders have a radius of 10 mm.

Geometry information and a set of material behaviour rules are contained in each of the created parts in the Abaqus simulation. Homogeneous, solid sections are used to define the section properties of the sheet metal. The specified material type is steel DC04 according to DIN EN 10130 standard [36]. The material's mass density is 7.8×10^{-9} tonne/mm^3, Young's modulus is 210,000 MPa, and Poisson's ratio is 0.3. The selected type of interaction is the surface-to-surface contact, which describes the contact between the sheet metal as a deformable surface and the forming tools as rigid surfaces. Considering the different surface roughness, the general contact with a Coulomb friction coefficient equal to 0.15 was selected for the interaction between the sheet metal and the forming tools. The boundary conditions are then used to specify the loading and interaction between the sheet metal's surface and the forming tools, guaranteeing that the sheet metal deforms appropriately. The appropriate selection of finite element formulation, element size, and the number of integration points through the sheet metal's thickness is critical for the analysis's accuracy and prediction of the sheet metal's behaviour. Fig. 9 shows the variable number of elements in different regions over the sheet's metal thickness. An increased number of 5 elements through the thickness of the sheet metal is used in the region where it undergoes elasto-plastic deformation and comes into contact with the forming tools. The meshed specimen consists of a total number of 11,088 nodes and 8,700 elements. The elements consist of 1,800 linear hexahedral elements of type C3D8R and 6,900 linear hexahedral elements of type C3D8I. Considering the symmetry conditions, only a quarter of the sheet metal needs to be modelled. The FEM is simplified as a result, and the computing time is reduced. The symmetry boundary conditions are applied to the highlighted surfaces of the sheet metal, as shown in Fig. 9.

During the loading phase, the forming tools move with a velocity of 30 mm/s in both vertical and horizontal directions. The displacement of the forming punch, s_p, and the displacement of the support cylinders, s_c, is different in each FEM simulation, as shown in Table 1. Depending on the displacement and the velocity of the forming tools, the time of forming punch, t_p, the time of support cylinders, t_c, and the total forming time, t_{tot}, required for completing the bending process have different values.

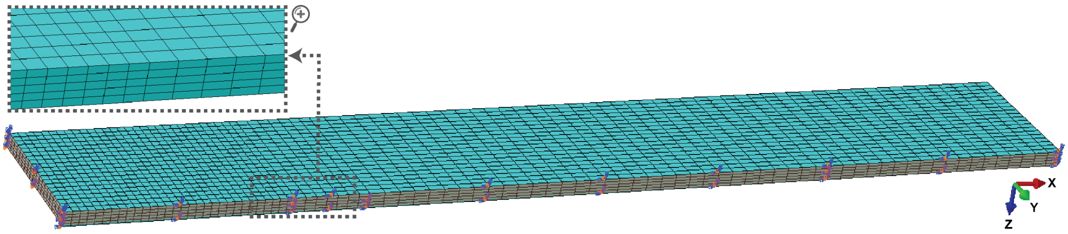


Fig. 9 Symmetry boundary conditions and assigned mesh on the sheet metal for the three-point bending analysis

Table 1 Combination of process parameters used in the three-point bending FEM simulations

No.	s_p (mm)	s_c (mm)	t_p (s)	t_c (s)	t_{tot} (s)
1	14	30	0.46	1	1
2	15	30	0.5	1	1
3	15.65	30	0.52	1	1
4	16	30	0.53	1	1
5	17	30	0.56	1	1
6	22.5	20	0.75	0.67	0.75
7	23.5	20	0.78	0.67	0.78
8	24.08	20	0.8	0.67	0.80
9	25.5	20	0.85	0.67	0.85
10	26.5	20	0.88	0.67	0.88
11	34	10	1.13	0.33	1.13
12	35	10	1.16	0.33	1.16
13	37	10	1.23	0.33	1.23
14	37.47	10	1.24	0.33	1.24
15	38	10	1.26	0.33	1.26
16	48	0	1.6	0	1.6
17	49	0	1.63	0	1.63
18	49.68	0	1.65	0	1.65
19	50	0	1.66	0	1.66
20	51	0	1.7	0	1.7

2.2 Computer-aided design

The three-point bending system is designed using the computer-aided design program SolidWorks, which involves sketching and adding dimensions to specify the geometry and position of all the components. The horizontal plate at the bottom supports the two vertical plates on which the linear systems are mounted. One linear system consists of two forming tools for supporting and bending the sheet metal in a horizontal direction, whereas the second linear system only has one forming tool for bending the sheet metal in a vertical direction. The connected stepper motors enable the moving and positioning of the forming tools fixed on the linear systems. The sheet metal is inserted underneath the forming punch and on the movable support cylinders. The three-dimensional (3D) model of the bending device with the linear systems that perform the bending of the sheet metal in the vertical and horizontal direction is shown in Fig. 10.

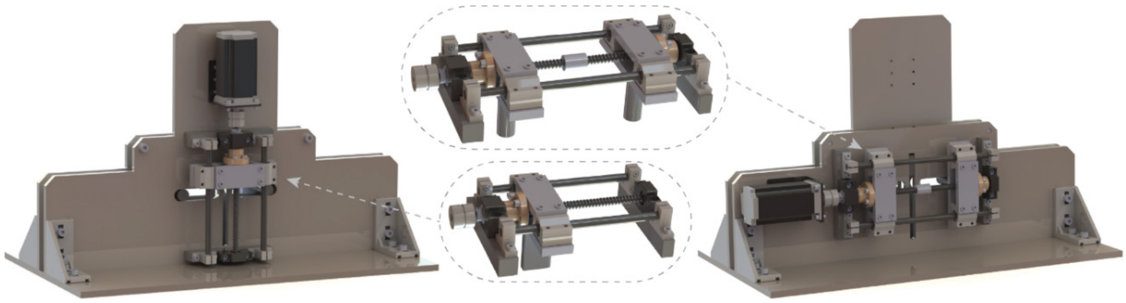


Fig. 10 3D model of the bending device with the vertical and horizontal linear systems

3. Results and discussion

This section presents the obtained results of the numerical approach and a comparative analysis for evaluating the findings' reliability. The finite element analysis was utilized to simulate the three-point bending process numerically. The findings of the numerical simulations were used to determine all specifications and requirements for the prototype development of the flexible tooling system.

3.1 Numerical simulation results

The influence of the process parameters on the sheet metal bending operation was studied by comparing the numerical results of 20 FEM simulations. The numerical simulations were conducted to identify the appropriate combination of process parameters for obtaining a 90° bent angle of the specimen after springback. The following influential process parameters were analyzed: bending angle before springback, α_1, bending angle after springback, α_2, angle difference before and after springback, $\Delta\alpha$, the maximum forming force of the forming punch, F_p, the maximum forming force of the support cylinders, F_c, displacement of the forming punch, s_p, displacement of the support cylinders, s_c, and total forming time required for completing the bending process, t_{tot}.

In the first set of numerical simulations, the range of the forming punch displacement is from 14 mm to 17 mm, and the displacement of the support cylinders is 30 mm. The second set has a range of forming punch displacement from 22.5 mm to 26.5 mm, and the displacement of the support cylinders is 20 mm. In the third set, the range of the forming punch displacement is from 34 mm to 38 mm, and the displacement of the support cylinders is 10 mm. In the fourth set, the support cylinders are fixed in their initial position, and the distance between them is 106 mm, whereas the range of the forming punch displacement is from 48 mm to 51 mm. Fig. 11 presents the various bending angle after springback, α_2, obtained for different combinations of the forming tools' displacement. It can be seen that the bending angle after springback, α_2, increases linearly by increasing the displacement of the forming punch, s_p. The desired bending angle after springback is 90° ±0.05° when the displacement of the forming punch is 15.65 mm, 24.08 mm, 37.47 mm, 49.68 mm, and the displacement of the support cylinders is 30 mm, 20 mm, 10 mm, 0 mm respectively.

Fig. 12 shows the relationship of the angle difference before and after springback, $\Delta\alpha$, and the bending angle after springback, α_2. The numerical data show that when the forming force is released, the sheet metal returns towards its original shape by a few degrees due to the effect of springback. The overbending method is utilized to acquire the required bent angle by angularly bending the sheet metal over the specified angle and achieving the chosen final shape after the occurrence of springback.

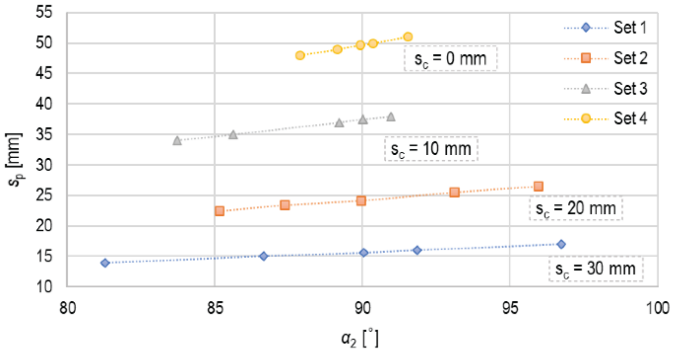


Fig. 11 Displacement of the forming punch, s_p, versus bending angle after springback, α_2, for different displacement of the support cylinders, s_c

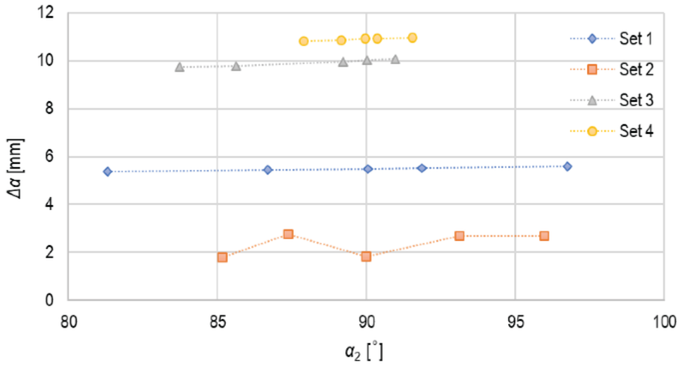


Fig. 12 The relationship of the angle difference before and after springback, $\Delta\alpha$, and the bending angle after springback, α_2

The total forming time, t_{tot}, is the sum of the time of forming punch, t_p, and the time of support cylinders, t_c, required for completing the bending process. During the loading phase of each numerical simulation, the forming tools move with a velocity of 30 mm/s in both vertical and horizontal directions. Fig. 13 presents the total forming time, t_{tot}, required to obtain the various bending angles after springback, α_2. In addition to the forming punch that performs the bending operation, two moveable support cylinders are employed in the sets with numbers 1, 2, and 3.

In the fourth set, the support cylinders are fixed in their initial position, and only the forming punch is moveable, resulting in a significantly longer total forming time necessary to complete the bending operation. In the first set, the range of the forming punch displacement is from 14 mm to 17 mm, while the displacement of the support cylinders is 30 mm in each of the numerical simulations. As a result, the support cylinders need longer time than the forming punch to reach the specified displacement, equal to the total forming time, t_{tot}, of 1 s. It can be concluded that a reduction of the total forming time can be achieved by implementing two moveable support cylinders in addition to the forming punch that performs the bending operation simultaneously. By reducing forming time, continuous quality improvements and better production efficiency can be achieved.

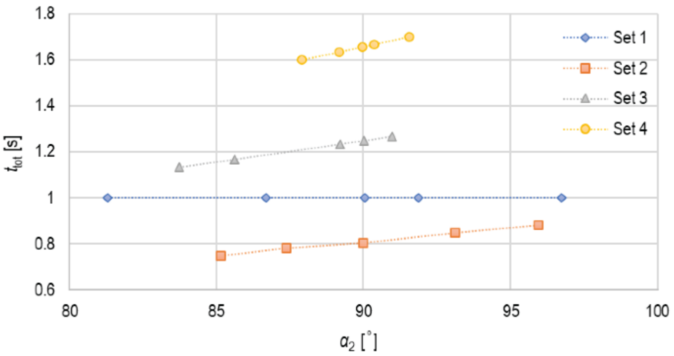
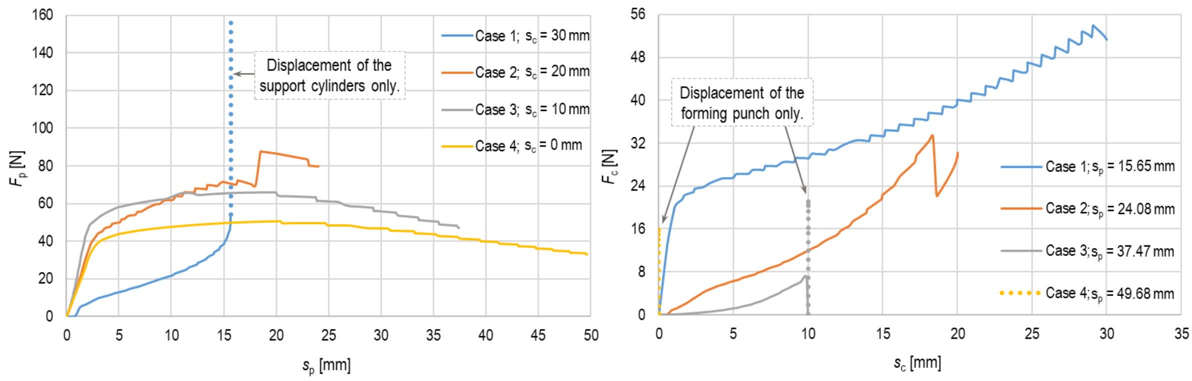


Fig. 13 Total forming time, t_{tot}, required for obtaining different bending angles after springback, α_2

The four cases of the FEM simulations for which the desired bending angle after springback is 90° ±0.05° are presented in Table 2. Fig. 14 shows the forming force evolution for different displacements of the forming tools in the cases when the bending angle after springback is 90° ±0.05°. The solid section of the curve represents the forming tools' movement, while the dotted section of the curve shows the condition in which the forming punch has already reached the specified displacement and the moveable support cylinders are still performing the bending process (Fig. 14a), or vice versa (Fig. 14b). During the sheet metal bending operation, force is applied on the specimen in the vertical direction by the forming punch and in the horizontal direction by the support cylinders. The amount of maximum forming force required to achieve a 90° bending angle after springback has been determined. Furthermore, knowing the maximum forming force contributes to improving the design of the flexible tooling system by selecting the stepper motors with the relevant key specifications. Additionally, the forming force required to bend the sheet metal is considered to be twice as large when selecting the stepper motor used to position two movable support cylinders.

Table 2 Variety of cases in which the bending angle after springback is 90° ±0.05°

Case	s_p (mm)	s_c (mm)	t_p (s)	t_c (s)	t_{tot} (s)	α_1 (°)	α_2 (°)	$\Delta\alpha$ (°)	F_p (N)	F_c (N)
1	15.65	30	0.52	1	1	95.53	90.04	5.49	157.69	53.89
2	24.08	20	0.8	0.66	0.8	91.82	89.98	1.84	87.79	33.28
3	37.47	10	1.25	0.33	1.25	100.04	90.01	10.03	65.93	21.78
4	49.68	0	1.66	0	1.66	100.86	89.95	10.91	50.83	16.25



a) b)

Fig. 14 Forming force evolution in the cases in which the bending angle after springback is 90° ±0.05°:
a) force of the forming punch, F_p, versus displacement of the forming punch, s_p;
b) force of the support cylinders, F_c, versus displacement of the support cylinders, s_c

Fig. 15 shows the relationship between the angle difference before and after springback, $\Delta\alpha$, and the total forming time, t_{tot}, in the cases in which the bending angle after springback is 90° ±0.05°. Analysis was carried out to evaluate the angle difference before and after springback throughout the simulations to define the appropriate process parameters for reducing springback and achieving the necessary final geometry of the part. The best process parameters that minimize the springback were identified in the second case by comparing the simulations' results in which the bending angle after springback is 90° ±0.05°. Springback is a critical challenge in metal forming, although by predicting and minimizing it using FEM simulations, it is feasible to improve the accuracy of the produced parts. Furthermore, ideal results are determined in the second case for the shortest time required to finish the bending process and obtain a bending angle of 90° ±0.05° degrees after springback.

By comparing the results obtained from the FEM simulations, the impact of various process parameters on the sheet metal bending operation is investigated. The second case in Table 3 has the process parameters of the optimal three-point bending FEM simulation. The specimen is bent to the required shape at a bending angle after springback of 90° ±0.05° degrees. The simulated bending angle before springback is 91.82°, and the bending angle after springback is 89.98°, thus resulting in 1.84° of springback.

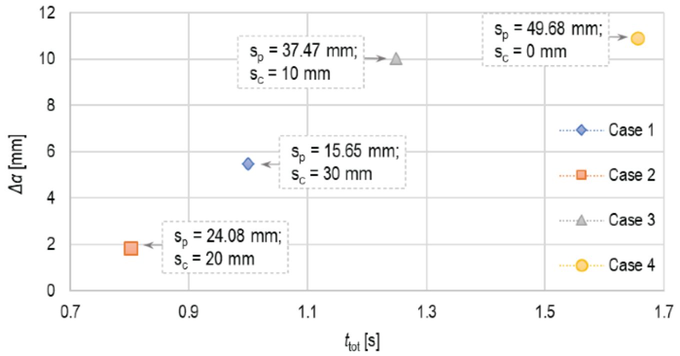


Fig. 15 The relationship of the angle difference before and after springback, $\Delta\alpha$, and the total forming time, t_{tot}, when the bending angle after springback is 90° ±0.05°

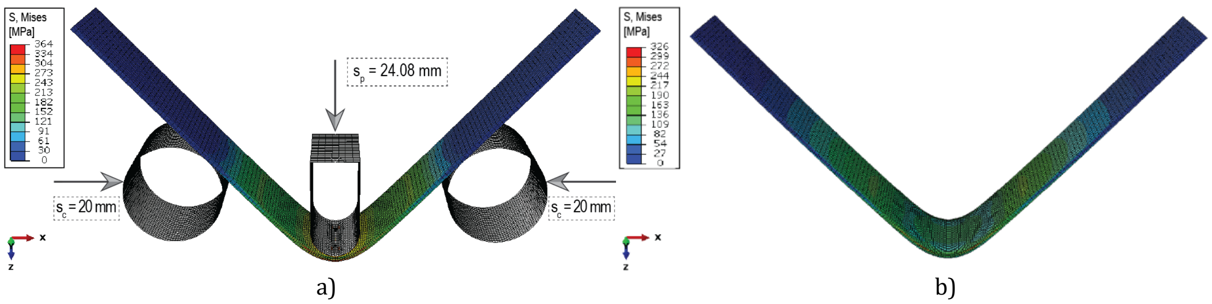


Fig. 16 Visualization of the three-point bending model: a) loading step; b) unloading step

The forming punch that bends the sheet metal in a vertical direction has a specified displacement of 24.08 mm and a maximum reaction force with a value of 87.79 N. The moveable support cylinders that bend the sheet metal horizontally from the left and right sides have a specified displacement of 20 mm and a maximum horizontal reaction force of 33.28 N. The total time required for the forming tools to reach the specified displacement for obtaining the desired bending angle after springback is 0.8 seconds. The sheet metal's behaviour at loading and unloading steps in the Abaqus simulation is shown in Fig. 16.

The numerical simulation results enabled the optimization of geometrical properties of the sheet metal, reduction of springback effect, and selection of the most dependable process parameters that are utilized as a reference for the design of the flexible tooling system. The obtained results show which process parameters are suitable for achieving the required 90° bent angle of the specimen after springback. It has been concluded that the flexibility of the three-point bending process is increased by the implementation of two moveable support cylinders in addition to the forming punch that performs the bending process. The appropriate forming tools' displacement and velocity during the bending process are identified to reduce processing time and increase process productivity. The computed maximum response force required for the forming tools to bend the sheet metal contributes to the comprehensive selection of stepper motors for a better design of the flexible tooling system for sheet metal bending.

3.2 Prototype development

The developed prototype of the bending device represents a preliminary version of a flexible tooling system for sheet metal bending, as shown in Fig. 17. The findings of the numerical simulations and the computer-aided design of the 3D model for the flexible tooling system were used to determine all specifications and requirements for the prototype development. The numerical simulations contributed to the identification of the optimal process parameters necessary for the production of sheet metal components with the desired shape. Furthermore, the 3D model's design enabled the visualization of the tooling system and the correct integration of the hardware and software components for effective system control. The prototype is created by integrating mechanical and electrical components, including Arduino Mega microcontroller, Nema 23 stepper motors, and digital stepper drivers. The stepper motors' movement is controlled by programming the Arduino microcontroller board to provide accurate displacement and regulate the speed of the forming tools. The Nema 23 stepper motors are driven by DM542T digital stepper drivers, which use logical inputs to pulse the motors and are suitable for their voltage and current requirements. To adjust the position of the motor shaft, the micro-stepping technique is used, which may enhance resolution and significantly increase motion stability [37]. Micro-stepping allows the stepper drivers to position the Nema 23 stepper motor shaft accurately by generating a step angle as small as 0.014° (25,600 steps per revolution). In addition, a switching power supply model S-350-24 is utilized in the prototype. The open-source Arduino Software – Integrated Development Environment (IDE) is used to write the code and upload it to the Arduino Mega 2560 microcontroller. The wiring connection of the Arduino microcontroller, the power supply, and the Nema 23 stepper motors with their micro-stepping drivers is shown in Fig. 17.

The prototype's functionality was evaluated after the development phase, and the bending method was successfully completed. To conduct an accurate comparison of numerical and experimental data, several areas for future improvement of the currently developed flexible tooling system have been identified. Closed-loop automation, which enables improved process control, and the use of appropriate sensors allowing real-time monitoring of the bending angle throughout the bending operation, are the most significant advancements.

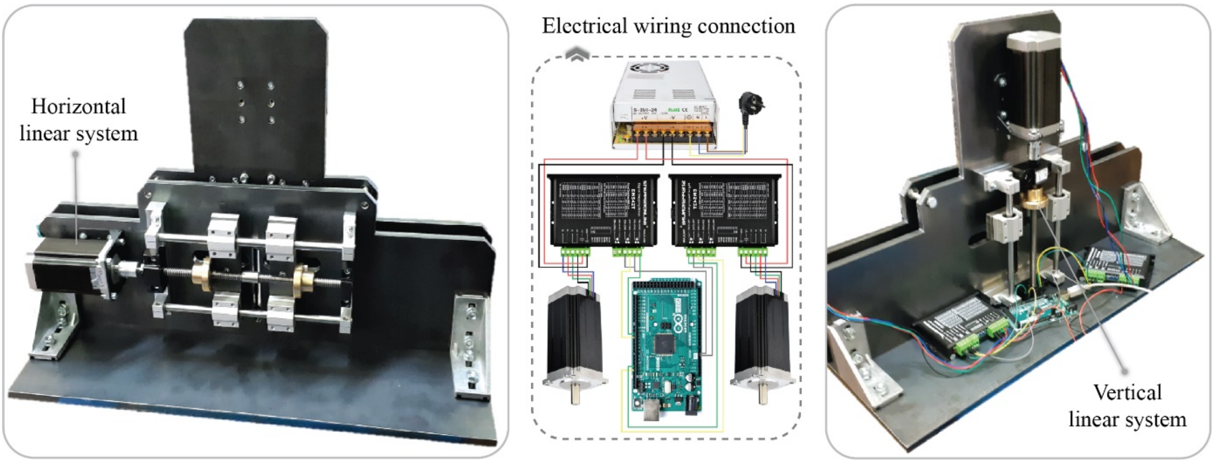


Fig. 17 Developed prototype of the flexible tooling system for sheet metal bending

4. Conclusion

Sheet metal bending processes are of crucial importance because they are widely applied for the manufacturing of various products, the majority of which are used in the automotive and aerospace industries. Since industrial requirements are rapidly increasing, the development of new methods for optimizing the bending process of sheet metals is in great demand. As a result, traditional metal forming tools are continuously being upgraded with novel technologies that can capture important data to improve the forming process. In this study, a novel flexible tooling system for optimizing process parameters and enhancing the sheet metal bending operation was developed.

The acquired results from the final element analysis contributed to the determination of the set-up and the geometry of the forming tools that are essential for obtaining the desired final shape of the bent sheet metal. The impact of various process parameters is evaluated by comparing simulation results, and the optimal three-point bending FEM simulation is selected. The most significant findings obtained from the performed numerical analysis are:

- The performed finite element analysis enabled the accurate prediction of the springback, which is 1.84° in the optimal three-point bending simulation.
- In addition to the forming punch that performs the bending process at the shortest production time with a displacement in a range from 22.5 mm to 26.5 mm, the innovative implementation of the moveable support cylinders with a displacement of 20 mm resulted in

greater flexibility of the bending process.
- The generated results indicate that the appropriate forming tools' displacement for obtaining the desired bending angle of 90° ±0.05° is 24.08 mm for the forming punch and 20 mm for the support cylinders.
- The determination of optimal displacement for the forming punch and the moveable support cylinders that move with a velocity of 30 mm/s during the bending process provided a reduction of processing time and improvement of process productivity for 48%, compared to the traditional three-point bending only with a movable forming punch.
- The applied overbending technique helps to eliminate the effect of springback occurrence by angularly bending the sheet metal for 1.84° over the required angle and achieving the desired angle of 89.98° after the forming force is released.
- The calculated maximum vertical force of 87.79 N and maximum horizontal force of 33.28 N required for the forming tools to bend the sheet metal aided in the selection of stepper motors for the design of the flexible sheet metal bending tooling system.

By predicting the influence of different process parameters using the numerical method, the essential data are acquired and incorporated into the design of a flexible tooling system for sheet metal bending. The following are the key characteristics of the developed flexible tooling system:

- Operating as an automated system capable of adjusting the forming tools' position and precisely controlling the bending process.
- Production of bent sheet metal parts with high quality and accuracy.
- Performance of continuous, well-structured, and rule-based forming operations.
- Run with high stability and dependability, reducing the occurrence of failures.
- The ability to bend sheet metals at various angles and thickness levels.

The expected results and the scientific contributions of the proposed research are focused to cover the most important, original, and innovative aspects of the following fields:

- Developed flexible tooling system for sheet metal bending that does not yet exist. The flexible tooling system aims to increase the efficiency of the forming process and reduce manufacturing disturbances.
- Significantly improved processing speed compared to the traditional three-point bending only with a movable forming punch, which is achieved by the innovative implementation of the moveable support cylinders.
- Designed flexible tooling system for sheet metal bending that has the potential for further implementation of sensors and upgrade of the controlling algorithm that can be utilized to process and analyse signals in real time. Those processed data will enable the prediction of potential deviations in bending process parameters that impact the final quality of the formed product and support the corresponding reaction of the actuators connected to the forming tools to eliminate potential errors.

Several areas can be recommended for potential improvement of the currently developed flexible tooling system, such as:

- Closed-loop automation that will enable advanced control of the forming process variables to the desired outcome without the need of human assistance.
- Implementation of appropriate sensors that will allow real-time measurement of the bending angle during the bending operation.
- Improvement of the currently developed flexible tooling system that will establish a connection between the FEM tools and the physical system for smooth data transfer between the cyber-physical system enabling online process monitoring and control.

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