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Force-Controlled Path Planning for Robot-Assisted Incremental Sheet Metal Forming: A New Approach to Addressing Dimensional Accuracy Challenges

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Abstract: Incremental sheet metal forming (ISMF) is a promising manufacturing technique that has gained significant attention due to its ability to produce complex geometries and high-quality products, particularly for small-scale production and rapid prototyping. The integration of industrial robots into the ISMF process, referred to as roboforming, has enabled advancements in this field. However, the inherent limitations of industrial robots—particularly the reduced rigidity of robotic arms with rotary joints—can lead to dimensional inaccuracies and deviations in the final product. These limitations are primarily due to the lack of precise force control during the forming process. To address these challenges, this study introduces a novel approach to roboforming that incorporates force control alongside the position control of the industrial robot. The contact force between the tool and the workpiece is considered as an additional variable in the control loop, with the objective of improving dimensional accuracy and the overall quality of the formed product. A regression analysis was conducted to determine the mean process force required for conical geometries, with the starting radius, infeed depth, wall angle, and supporting angle serving as input variables. Experimental validation revealed that force-controlled incremental forming with a constant contact force is unfeasible, as the pressure force is highly dependent on the current radius of the workpiece and varies during the forming process. Therefore, a new control strategy is proposed, which involves the dynamic adjustment of the contact force, using the variable pressure force as an input parameter. This approach is expected to significantly enhance the precision and reliability of robot-assisted ISMF, offering a pathway for overcoming current limitations in industrial applications.

Keywords: Incremental sheet metal forming (ISMF); Industrial robots; Roboforming; Force control; Dimensional accuracy; Pressure force; Regression analysis; Process optimization

1 Introduction

Due to market trends that have prevailed since the beginning of the 21st century, such as the increase in the number of product variants and their shorter life cycle, it is necessary to make adjustments, both in the products themselves and in the production technologies. At the same time, it is necessary to achieve greater speed and flexibility in product development, which implies economical production of individual products (size of series 1) in the future [1–3]. One of the basic prerequisites to meet these requirements is the development of innovative production systems.

One of the areas with great potential for improving the productivity and speed of manufacturing products in smaller series is ISMF. In contrast to classical forming methods, which involve the development of expensive tools and molds, in ISMF, smaller processing forces occur, and it is possible to use universal tools in the form of tips due to limited deformations that occur gradually during forming. CNC machines or industrial robots can be used for this type of shaping as very flexible devices whose movement can be easily programmed [1, 4].

One of the directions of research of ISMF is the so-called roboforming, a process involving two heavy-duty industrial robots, between which a sheet metal to be formed is held in a fixed frame. By synchronizing their movements, the robots gradually shape the product using universal tools attached to their arms [5]. One of the first work cells to perform the roboforming process was implemented at the Department of Manufacturing Systems (LPS) of the Ruhr University in Bochum.

The main disadvantage of roboforming is the structure of the industrial robot with rotary joints, which is characterized by reduced rigidity. Since the contact forces that occur in the forming process can be quite large, due to the elasticity of the joints there may be deviations in the tool movement from the programmed path, which leads to errors in the shape and accuracy of the product dimensions. Therefore, in the past period, various methods for so-called stiffness compensation have been implemented, with the help of which the tool path correction is calculated based on information about deformations during the process. Compensation calculations can be performed before the forming process itself (offline method) [6, 7] or online [8, 9] based on instantaneous information obtained from force sensors during the process.

By applying stiffness compensation methods, the accuracy of product manufacturing in ISMF is increased, but it has not yet been brought to the desired level, especially with complex geometries. The main reason for this was the demanding calculations during the process itself and the communication between the robot control unit and the external computer on which these calculations were performed. This would often lead to the robot control unit being unable to perform the set movement task, which in complex geometries with small curvature radii caused the appearance of larger manufacturing errors.

Another method for improving formability is hot forming, in which the sheet metal is heated during the forming process [10, 11]. Heating can be applied to the entire sheet using a heating device [12], or it can be localized to the specific area being formed. For localized heating, two approaches are commonly used: a laser beam directed slightly ahead of the tool on the back of the sheet [13] or conductive heating, where the tool and sheet act as voltage poles, and the heat generated by the current flow at the forming tip is transferred into the material [10].

Both methods reduce forming forces by softening the material and decreasing the subsequent deformation and rebound strength due to lower mechanical stresses. This enhanced formability makes hot forming suitable for processing hard-to-form materials and thicker sheets compared to forming at room temperature [10, 13]. However, the main disadvantages of these techniques include complex control schemes, potential risks of current flow through the parts being formed, and the possibility of overheating robot components.

Numerous studies have investigated modeling the contact force as a function of process parameters for various applications. These modeling efforts primarily rely on numerical simulations [14], experimental studies [15], or artificial intelligence methods [16]. Additionally, several implementations of force control in ISMF can be found in the literature [17–19]. However, these implementations are not directly related to the force control of the master robot responsible for shaping and do not employ explicit force control models.

The objective of this paper is to develop a force control scheme for the master robot in the roboforming process. This scheme will be based on an experimentally derived force model tailored for specific conical-shaped products.

To address this issue, it is essential not only to enhance the existing processing methods but also to develop and evaluate new strategies for implementing an ISMF process supported by industrial robots. This paper introduces a roboforming method that integrates position control of the industrial robot with force control, incorporating the contact force between the tool and the workpiece as an additional variable in the control loop. For this method to be effectively applied, it is first necessary to investigate the forces generated during the process, drawing on prior research and conducting additional experiments.

2 Methodology – Experimental Setup

For research in the field of robot-based ISMF, the Department for Production Systems (LPS) at the Ruhr University Bochum has developed a test facility (see Figure 1). The heavy-duty industrial robots, measuring devices, and other inventory required for the forming are located in this system within a fence that has been attached for safety reasons. There are two KUKA KR600 robots and two KUKA KR360 robots. The latter are robots that were used for the experiments from the previous chapter, while the former are used for the upcoming research (see 1 and 2 in Figure 1) and are therefore described below.

For roboforming, the two KUKA KR600 robots are networked to form a so-called KUKA RoboTeam. This allows the robots to carry out cooperative transformations during the process through synchronous movements. One of the two takes over the active sheet metal forming, and it is called the master. The task of supporting is carried out by the other robot, called the slave.

The two KUKA KR600 robots have the appropriate tools for sheet metal forming, which are attached to the flange, with an FT-NET Omega191 force/torque sensor from SCHUNK GmbH & Co. KG positioned between them. The sheet metal to be formed is fixed in a clamping frame (see 5 in Figure 1), which is anchored in the floor between the two industrial robots and divides the spatial distance between them into roughly two halves of the same size. Specifically, both KR600 are about 2262 mm away from the clamped sheet metal part with a laterally offset of about 628 mm from the center of the frame window. This prevents possible singularities of the robot during the forming movements. Due to its structural design, the clamping frame itself allows sheet metal of various sizes to be fixed, which can range from 220 mm × 220 mm to 1500 mm × 600 mm. Figure 2 visualizes the frame structure and the robot's forming tool in front of it.

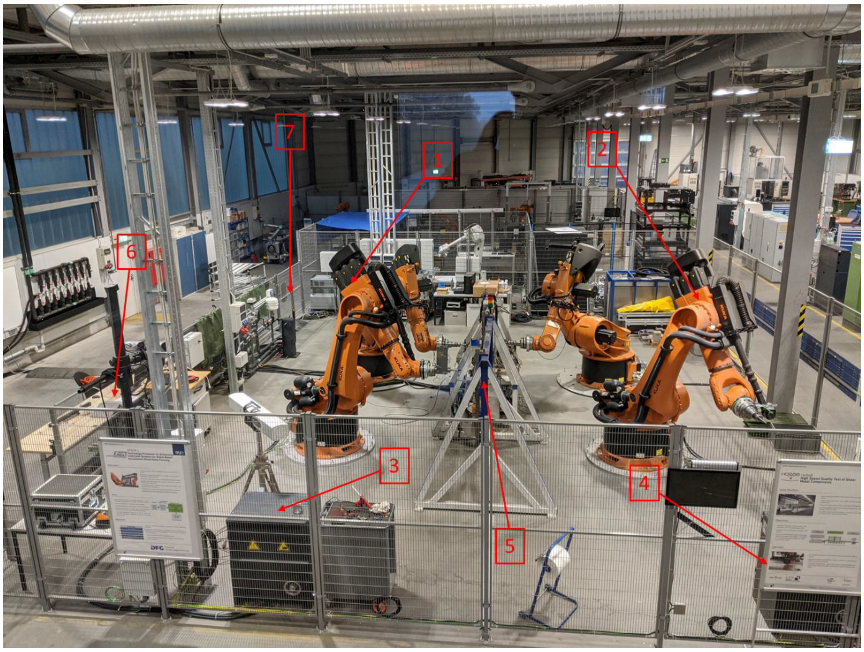

Figure 1. Roboforming cell used for the experiments [19]

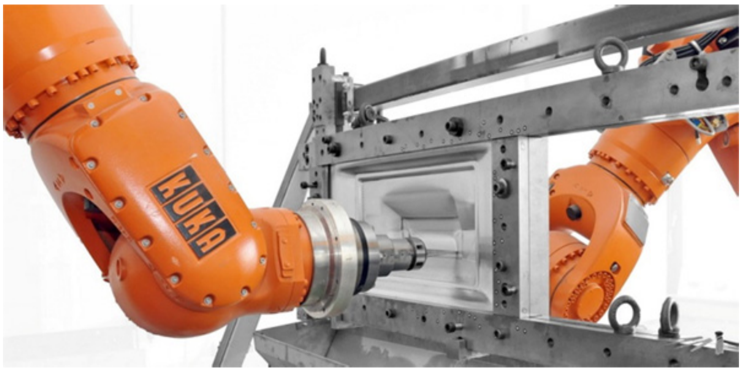

Figure 2. Roboforming process [20]

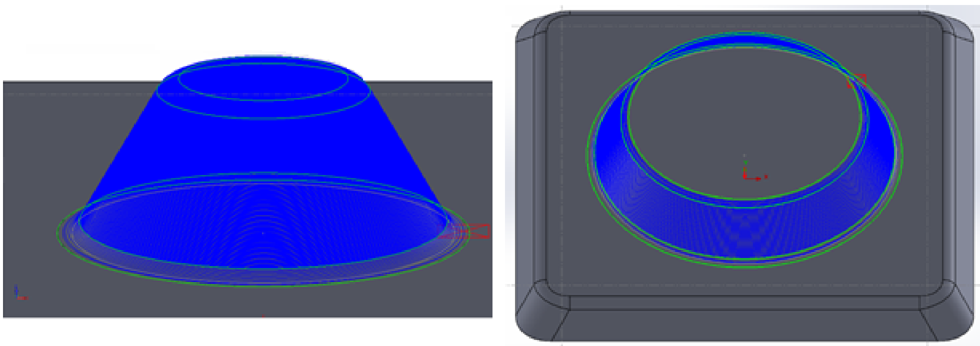

Figure 3. Base geometries for experiments with different start radii and wall angles

The test facility also contains the KR C4 controllers connected to the robots by cable (see 3 and 4 in Figure 1). This in turn is followed by the handheld programming device to be used by the user. All of these devices are surrounded by the aforementioned safety fence, which has two entrance doors, and all these devices are part of the roboforming cell. The process control computer used for stiffness compensation and force control is positioned outside the cell. The roboforming process is illustrated in Figure 2.

In order to examine the pressure force by robot-based incremental sheet forming with the accent to the radius of the workpiece, a set of input variables was defined. Conical geometries with different starting radii and wall angles were used as base geometries. Some examples of base geometries are shown in Figure 3.

Supporting angle and infeed depth are chosen as further input variables, making the set of input variables as follows:

1. Starting radius of cone [mm], X_1
2. Infeed depth [mm], X_2
3. Wall angle [°], X_3
4. Supporting angle [%], X_4

According to the previous research in the field of robot-based ISMF [20, 21], upper and lower limits for input variables were determined, and a Placket-Burmann experimental plan with 8 experiments was designed (see Table 1).

Table 1. Experimental plan for definition of pressure force

Exp. No.	X_1 **Starting Angle** [mm]	X_2 **Infeed Depth** [mm]	X_3 **Wall Angle** [°]	X_4 **Supporting Angle** [%]	Y **Pressure Force** [N]
1	70	0.1	30	0.1	566.07
2	70	0.6	30	0.9	822.88
3	70	0.6	60	0.1	654.45
4	30	0.6	60	0.9	593.37
5	70	0.1	60	0.9	512.43
6	30	0.6	30	0.9	721.35
7	30	0.1	60	0.1	388.57
8	30	0.1	30	0.1	488.91

For each experiment, the geometry of the workpiece and tool path were defined according to the input parameters for both the master and slave robots using appropriate software (Solidworks, Autocam); see Figure 3. The main output parameter for the analysis was the pressure force (Y). The experiments were executed with the current online stiffness compensation control schema. Through the RSI connection with the robot, the online data from the 6-axis force/torque sensor, mounted on the robot wrist, during the processing were collected. After the execution of every single experiment, the active pressure force was examined and its mean value was calculated. Mean values of the pressure force are also given in Table 1.

The above-mentioned 6-axis force/torque sensor FT-NET Omega191 is also one of the central parts of the force control schema that is implemented in the roboforming process. For real-time process control, an external controller is implemented using the MATLAB Simulink Real-Time module, hosted on an industrial computer located outside the robot work cell. Communication with the robot control units is facilitated by a KUKA Robot Sensor Interface (RSI) operating with an interpolation cycle of 4 ms (the time interval between consecutive data readings). Using the RSI, real-time correction of the robot's position is performed based on sensor data, with corrections applied in the subsequent interpolation cycle.

The external computer is connected to both robots in the roboforming cell via Ethernet and communicates using the UDP protocol. The robots transmit data to the computer regarding their current positions and contact forces measured by sensors. Simultaneously, the desired force values are set in the real-time module on the external computer. Based on this data, the robot system model calculates position corrections for the robot arm in the direction of the tool's action. These corrections are then transmitted to the robot control units.

While the stiffness compensation method primarily applies force control to the slave robot, in the presented scheme, force control is applied to the master robot, which directly performs the forming process. During the forming operation, the robots follow a spiral tool path, calculated for each process step using the Autocam software module. The tool path consists of individual points connected by linear movements, ensuring precise execution of the forming task.

3 Results

3.1 Model of the Pressure Force by Robot-Based ISMF

After the execution of every single experiment, the active pressure force was examined and its mean value was calculated. Mean values of the pressure force are also given in Table 1.

Using the obtained data, a regression model was established, which predicts mean pressure force for a given set of input parameters. The best fit model (R-squared = 0.9949; adjusted R-squared = 0.988) was obtained through linear regression. In this case, the equation describes the influence of input parameters on pressure force:

$$Y = 490.17 + 2.27 \times X_1 + 373.37 \times X_2 - 3.75 \times X_3 + 55.83 \times X_4 \tag{1}$$

The time flow of the pressure force during processing was also recorded for each experiment, and results for experiments No. 5 and 8 are given in Figure 4.

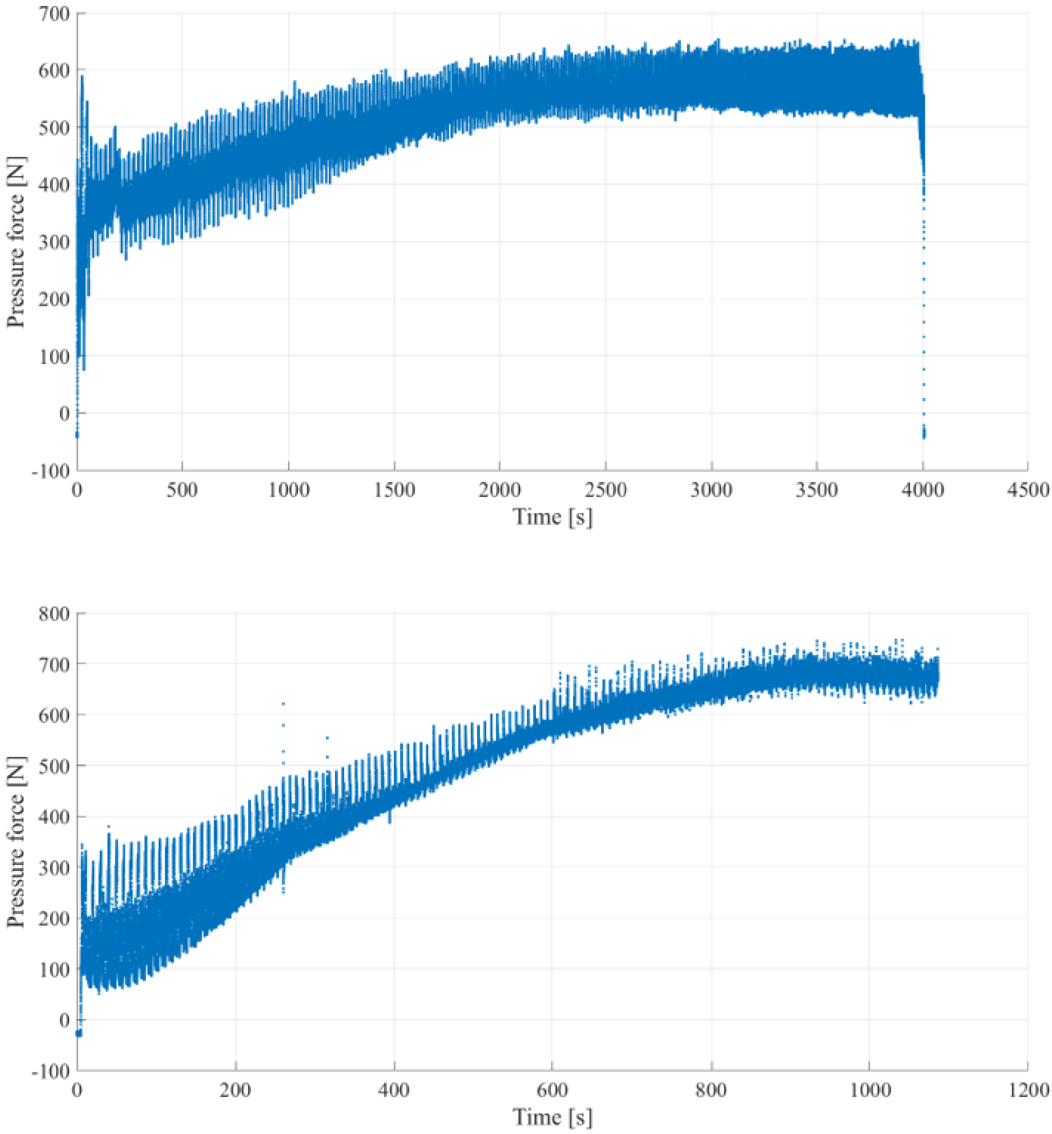

Figure 4. Time flow of the pressure force for experiments No. 5 (above) and 8 (below)

3.2 Experiments with Force Controlled ISMF

On the basis of results and experiments from Section 3.1, it was planned to conduct a series of experiments with a new control strategy. A hybrid force-position control of the robot was applied to the ISMF process (see Figure 5).

This schema was implemented with the help of MATLAB software on an external computer with online real-time communication with the robot control unit. As input parameters, the same workpiece geometries (cone) and parameters from Table 1 (starting radius of the cone, infeed depth, wall angle, support angle) were used. As constant input pressure forces were used, the mean pressure forces from experiments (see Table 1). The diagrams in Figure 4 show that the measured forces along the tool path in the experiments without force control are lower in the first part of the process and increase during the processing time.

The implementation of a control scheme using a constant mean pressure force resulted in an initial force greater than what was necessary for deformation. This caused excessive deformation of the workpiece at the start of the process, accompanied by tool vibrations. Adjusting the input force to a lower level improved the initial shaping process; however, maintaining a constant force throughout the operation proved insufficient for continued deformation. As a result, the tool merely slid over the surface of the workpiece. In both scenarios, the product became severely warped, making it impossible to measure deviations from the intended geometry.

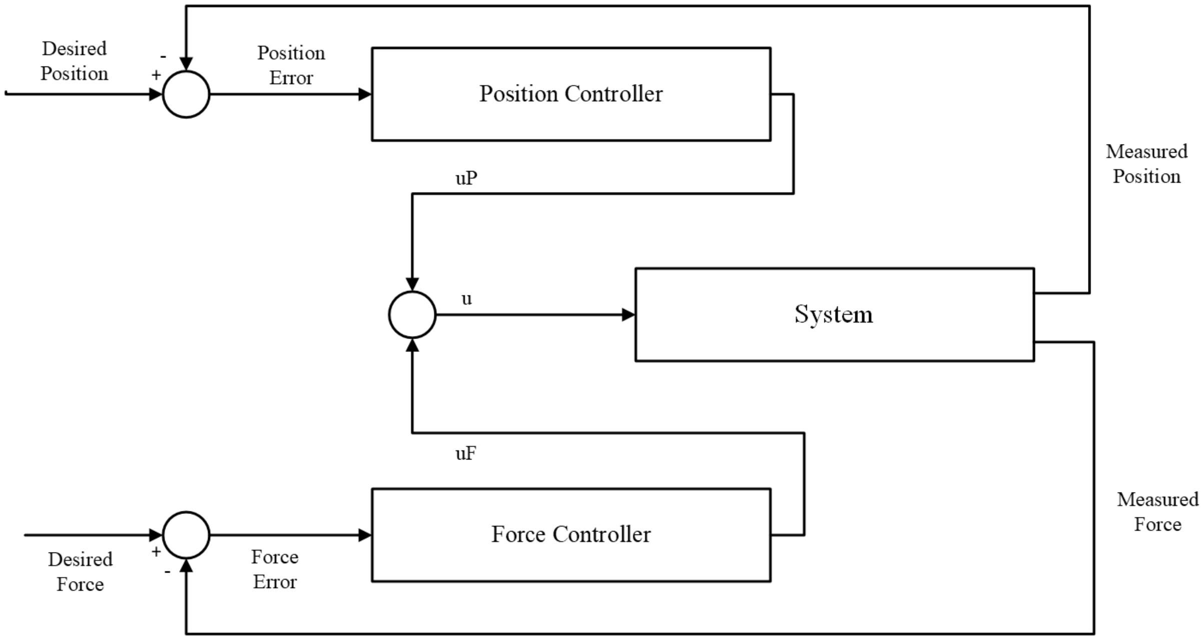

Figure 5. Hybrid force-position control of robot [22]

4 Discussion

Unfortunately, planned experiments could not be executed as wished. The reason for that is the fact that the pressure force is strongly dependent on the current radius of the workpiece, and it changes its value during processing (see Figure 4). Therefore, the processing with the constant pressure force was not possible. The used mean value was higher than the value of the pressure force at the beginning of the processing, causing strong vibrations of the system that could not be eliminated by changing the controller parameters. By usage of lower input forces, the forming process could not be brought to the end, and the desired end shape of the workpiece could not be obtained.

This problem can be solved by establishing a complex model with the current workpiece radius as one of the important input values, and that will be the topic of further research in this field. A new control schema also has to be developed, using variable pressure force as an input parameter instead of a constant one. A very useful tool for the development of a new control schema could be methods of artificial intelligence (e.g., multilayer artificial neural networks).

5 Conclusions

Trying to implement a new force control schema in order to improve the quality of products obtained by robot-based ISMF, in a first step a new mathematical model, describing the dependence of the mean pressure force on the process parameters, was developed. In order to determine the influence of input process parameters (starting radius of cone, infeed depth, wall, and supporting angle) for a specific geometry of workpiece (cone), an experimental plan with 8 experiments was designed. The obtained linear regression model with high R-squared and adjusted R-squared values (0.9949 and 0.988, respectively) ensures a very precise interpolation and prediction of a mean contact force during the forming process. A hybrid force-position robot control schema was implemented with constant pressure force as an input parameter based on those experiments. However, the application of the force control showed that it was not possible to successfully implement the schema with constant pressure force because the force during processing was variable and dependent on the current radius of the workpiece.

Therefore, future research in this field should include building a model (e.g., with the help of artificial intelligence methods), which describes the dependence of the pressure force on the current workpiece radius, whereby the mean contact force cannot be used as an input parameter. It is necessary to develop a new control schema with variable pressure force, defined for each point on the tool path. A large database with the data from previous experiments conducted in the robot work cell for ISMF at the Department of Manufacturing Systems in Bochum can be used as a good base for the training of multilayer artificial neural networks for the prediction of the contact force along the tool path in the forming process.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] H. Meier, V. Smukala, and B. Buff, "Roboterbasierte inkrementelle Blechumformung: Bauteilgenauigkeitssteigerung in einem automatisierten industriellen Gesamtkonzept," *wt Werkst. Online*, vol. 98, no. 10, pp. 831–836, 2008. https://doi.org/10.37544/1436-4980-2008-10-831

[2] P. Groche, M. Kraft, S. O. Schmitt, U. Lorenz, S. Pokutta, A. Martin, and N. Ziems, "Rechnet sich flexibilität in der umformtechnik? Ein wirtschaftlicher Vergleich konventioneller und flexibler umformanlagen," *wt Werkst. Online*, vol. 100, no. 10, pp. 734–742, 2010.

[3] E. Uhlmann, "Wandel der fabrik durch produkt-individualisierung," in *Marktchance Individualisierung*. Springer, Berlin, Heidelberg, 2003, pp. 119–127. https://doi.org/10.1007/978-3-642-55495-7_11

[4] D. Kreimeier, V. Smukala, C. Magnus, B. Buff, and J. Zhu, "Kraftgeregelte umformung im roboforming: Einfluss aufbauteilgenauigkeit, oberflächenqualität und multimodale geometrien," *wt Werkst. Online*, vol. 100, no. 10, pp. 772–778, 2010. https://doi.org/10.37544/1436-4980-2010-10-772

[5] "Roboforming - Roboterbasierte Blechumformung komplexer Bauteile in kleinen Stückzahlen," Ruhr-Universität Bochum, Germany, 2007. https://ips.mb.tu-dortmund.de/forschen-beraten/forschungsprojekte/abgeschlossene-projekte/roboforming/

[6] J. Zhu, "Simulation of the load-dependent tool path deviations in robot based incremental sheet metal forming," Master's thesis, Ruhr-Universität Bochum, Germany, 2009.

[7] J. Kang, "Weiterentwicklung und experimentelle verifikation eines modellbasierten Ansatzes zur Genauigkeitssteigerung in der roboterbasierten inkrementellen Blechumformung," Master's thesis, Ruhr-Universität Bochum, Germany, 2010.

[8] R. Laurischkat, *Kompensation Prozesskraftbedingter Bahnfehler bei der Roboterbasierten Inkrementellen Blechumformung*. Germany: Shaker Verlag, 2012.

[9] T. Gorlas, "Entwicklung einer Steifigkeitskompensation für die roboterbasierte inkrementelle Blechumformung," Master's thesis, Ruhr-Universität Bochum, Germany, 2020.

[10] C. S. Magnus, "Lokale joulesche Erwärmung der Umformzone in der roboterbasierten inkrementellen Blechumformung," Ph.D. dissertation, Ruhr-Universität Bochum, Germany, 2015.

[11] L. Thyssen, *Kompensation von Erwärmungsbedingten Bauteilabweichungen in der Lokal Erwärmten, Roboterbasierten Inkrementellen Blechumformung*. Germany: Shaker Verlag, 2020.

[12] G. Ambrogio, L. Filice, and G. L. Manco, "Warm incremental forming of magnesium alloy AZ31," *CIRP Ann.*, vol. 57, no. 1, pp. 257–260, 2008. https://doi.org/10.1016/j.cirp.2008.03.066

[13] J. R. Duflou, B. Callebaut, J. Verbert, and H. De Baerdemaeker, "Improved SPIF performance through dynamic local heating," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 5, pp. 543–549, 2008. https://doi.org/10.1016/j.ijmachtools.2007.08.010

[14] K. Bensaid, R. Souissi, A. Boulila, M. Ayadi, and N. Ben Fredj, "Numerical investigation of incremental forming process of AISI 304 stainless steel," *Ironmak. Steelmak.*, vol. 50, no. 2, pp. 174–183, 2023. https://doi.org/10.1080/03019233.2022.2099695

[15] B. Saidi, A. Boulila, M. Ayadi, and R. Nasri, "Experimental force measurements in single point incremental sheet forming SPIF," *Mech. Ind.*, vol. 16, no. 4, p. 410, 2015. https://doi.org/10.1051/meca/2015018

[16] A. Alsamhan, A. E. Ragab, A. Dabwan, M. M. Nasr, and L. Hidri, "Prediction of formation force during single-point incremental sheet metal forming using artificial intelligence techniques," *PLoS ONE*, vol. 14, no. 8, p. e0221341, 2019. https://doi.org/10.1371/journal.pone.0221341

[17] D. Möllensiep, T. Gorlas, P. Kulessa, and B. Kuhlenkötter, "Real-time stiffness compensation and force control of cooperating robots in robot-based double sided incremental sheet forming," *Prod. Eng. Res. Devel.*, vol. 15, no. 5, pp. 683–699, 2021. https://doi.org/10.1007/s11740-021-01052-4

[18] H. Meier, C. Magnus, and V. Smukala, "Impact of superimposed pressure on dieless incremental sheet metal forming with two moving tools," *CIRP Ann.*, vol. 60, no. 1, pp. 327–330, 2011. https://doi.org/10.1016/j.cirp.2011.03.134

[19] H. Q. Ren, F. H. Li, N. Moser, D. Leem, T. M. Li, K. Ehmann, and J. Cao, "General contact force control algorithm in double-sided incremental forming," *CIRP Ann.*, vol. 67, no. 1, pp. 381–384, 2018. https://doi.org/10.1016/j.cirp.2018.04.057

[20] D. Störkle, P. Altmann, D. Möllensiep, L. Thyssen, and B. Kuhlenkötter, "Automated parameterization of local support at every toolpath point in robot-based incremental sheet forming," *Procedia Manuf.*, vol. 29, pp. 67–73, 2019. https://doi.org/10.1016/j.promfg.2019.02.107

[21] M. Čabaravdić, D. Möllensiep, B. Kuhlenkötter, and A. Hypki, "Analysis of pressure force in robot supported sheet metal forming," in *KOD: International Conference Machine and Industrial Design in Mechanical Engineering*, Novi Sad, Serbia, 2022, pp. 407–413. https://doi.org/10.1007/978-3-030-88465-9_39

[22] M. Raibert and J. J. Craig, "Hybrid position/force control of manipulators," *J. Dyn. Sys. Meas. Control.*, vol. 103, no. 2, pp. 126–133, 1981. https://doi.org/10.1115/1.3139652