MATEC Web of Conferences **408**, 01057 (2025) https://doi.org/10.1051/matecconf/202540801057
IDDRG 2025

Contributions to increasing the accuracy and reducing the forming forces of robot-based two-point incremental forming

Peter Scholz[1], *Dieter* Weise*[1], *Alexander* Pierer[1], *Christian* Naumann[1], *Martin* Dix[1, 3], *Marina* Terlau[2], *Axel* von Freyberg[2] and *Andreas* Fischer[2]

[1] Fraunhofer Institute for Machine Tools and Forming Technology IWU, Reichenhainer Straße 88, Chemnitz, 09126, Germany
[2] University of Bremen, Bremen Institute for Metrology, Automation and Quality Science, Linzer Straße 13, Bremen, 28359, Germany
[3] Chemnitz University of Technology, Straße der Nationen 62, 09111 Chemnitz, Germany

Abstract. This article presents the latest research results on the enhancement of robot-based incremental sheet metal forming performance in detail and comprehensively. Since the low robot stiffness leads to deformations of the robot and thus deviations of the final part, the presented contributions aim for increasing the part accuracy. The article demonstrates how an advanced sensor network, analogous to a µGPS, can be established for tracking the tool pose utilizing innovative shadow imaging sensor technology. Static experiments show that a measurement uncertainty below of 50 µm is achievable after the correction of systematic errors. Additional experiments demonstrated the applicability of the sensor network for measuring the tool position on a moving robot. Based on the measurement, a robot position correction will be enabled to achieve a reduction of machine-dependent component tolerances. A further approach to reduce the geometric deviations due to robot deformation is reducing the forming forces in robot-based two-point incremental forming. This is achieved by a modular vibration unit that has been specially developed for this purpose. The introduction of ultrasonic vibrations into the forming process has been shown to reduce the forces in the sheet metal plane by 70%. As a result, the sensor network and the introduction of ultrasonic vibrations provide a robust foundation for the advancement of higher accuracy classes with cost-effective robot technology, which is becoming increasingly crucial in the industry.

Keywords: incremental sheet metal forming; optical sensors; ultrasonic-assisted vibration-superimposed forming; forming equipment.

1 Introduction

Incremental Sheet Forming (ISF) has emerged as a promising manufacturing technology for the flexible and cost-effective production of sheet metal parts in small series and prototyping applications. Unlike conventional forming methods such as deep drawing, ISF eliminates the need for expensive tooling, resulting in significant cost savings and shorter development cycles. Instead, sheet metal is formed incrementally through localized deformation, enabling complex geometries [1].

With the growing adoption of automation and digitalization in manufacturing, the use of robots in ISF has gained increasing attention [2]. Robots provide high flexibility and low investment costs, which are essential for meeting the demanding requirements of modern manufacturing processes. However, challenges remain in the broader application of robotic technology in ISF, particularly concerning stiffness and the quality of the produced components [3]. These limitations are primarily caused by the low stiffness of industrial robots compared to dedicated machine tools and by process-related factors such as friction and force fluctuations.

To address these challenges, various software- and hardware-based approaches have been developed to enhance process performance and improve part quality. Techniques like optical position control [4] for stiffness compensation and the application of machine learning for optimizing process parameters can significantly enhance performance [5]. Furthermore, the effects of ultrasonic-assisted forming, known since 1955 [6], continue to be investigated to better understand their potential for stress and force reduction in sheet forming [7]. Despite these promising effects, the underlying mechanisms of ultrasonic assistance in ISF remain insufficiently understood and require further investigation [8].

This paper investigates the application of industrial robots for incremental sheet forming, with a focus on overcoming the limitations of robotic stiffness and improving part quality through innovative approaches. The proposed strategies of optical stiffness compensation through tool center point (TCP) correction using optical sensors, vibration-assisted forming, and the integration of ultrasonic technology, aim to advance robotic ISF and its potential for wider industrial applications.

1.1 Improved accuracy for robot-based forming

Industrial robots have been used for assembly tasks for decades. Using robots for cutting and forming tasks,

---

* Corresponding author: dieter.weise@iwu.fraunhofer.de

which generally have much higher accuracy requirements, is not directly possible. Due to the general kinematic structure of a robot, the geometric errors of the manufactured part are much larger than for standard Cartesian machine tools. For the same reason, the stiffness and load-bearing capacity are generally lower. Not only is the accuracy lower, but it is also highly position dependent. Furthermore, most industrial robots operate on robot controls, so the robot can repeatedly position to specified points in space with an uncertainty of about 50 µm but is not able to follow a specified trajectory.

Nevertheless, making such robots accurate enough for cutting and forming tasks is possible. Position control for defined trajectories can be achieved by replacing the robot control with a numerical motion control (CNC). The CNC handles the kinematic transformations and allows operating the robot like any other machine tool by running standard G-Code files. Static errors due to a lack of stiffness can be reduced by mapping the deflection for a large number of machine poses in the workspace [9, 10, 11], by simulation-based stiffness prediction [12] and using force sensors near the robot TCP [13].

A different and more versatile approach is the use of optical sensors to directly measure the robot tool position with the required measuring uncertainty and applying the measured position errors in real-time to the CNC. Sazonnikova et al. [14] adjusted the robot movement during an ISF process using a laser tracker. Laser trackers are, however, very expensive and make real-time compensation via control integration difficult. A novel measurement technology is the use of shadow imaging sensors, which was introduced by Grenet et al. [15] in 2015. Light-emitting diodes (LED) placed are fixed on the moving tool which is tracked via a set of stationary optical sensors. Each sensor contains a mask, possibly a colour filter and a photo-sensitive chip. Two or more sensors observing a single LED can determine a 3D position. A 6D pose, i. e. the position and orientation, can be obtained by using three coloured LEDs, which can be differentiated using colour filters [4]. Previous investigations have shown that such 6D pose measurements can be achieved using a shadow imaging sensor array with a measurement uncertainty of less than 50 µm translational and under 0.05° orientational error [4]. This paper expands on this work by demonstrating the practical application of the shadow sensor network during movement, such as a robot-held forming stylus during ISF processes.

1.2 Force reduction through vibration support

Ultrasonically assisted ISF combines the tool motion with an additional vibration component (linear or rotational) to enhance forming conditions by reducing friction, forming forces, and tool wear.

Vahdati et al. [16] demonstrated that ultrasonic assistance can reduce the mean forming force by up to 26% and surface roughness by up to 55%. Additionally, the forming accuracy of components was improved due to reduced spring-back effects. Li et al. [17] confirmed these findings through simulations, predicting that higher vibration amplitudes increase effective plastic strain and further decrease forming forces. R. Cheng et al. [18] found that the reduction in forming forces was more significant in Two-Point-Incremental-Forming (TPIF) compared to Single-Point-Incremental-Forming (SPIF) when ultrasonic assistance was applied. Yang et al. [19] identified optimal forming angles with a vibration amplitude of 6 µm and a frequency of 25 kHz. Z. Cheng et al. [20] reported a reduction in forming force by up to 67% with a vibration amplitude of 10 µm, along with a 50% decrease in contact surface stress. Microstructural investigations revealed an increased proportion of low-angle grain boundaries under ultrasonic conditions, which facilitated dislocation movement, reducing deformation resistance and forming forces. Wang et al. [21] focused on spring-back and showed that ultrasonic assistance significantly reduces this effect. However, the vibration amplitude should be adapted to the forming depth for effective spring-back suppression.

Preliminary work and patents by Fraunhofer IWU on vibration actuators in machining and peening are the foundation for the development of actuators as a separate tool adapter with hollow shank taper (HSK) interface for ISF, as demonstrated in this paper.

2 Methods and procedures

The two approaches - enhancing accuracy through the use of an optical sensor network and reducing force through vibration assistance - are analyzed separately below and integrated in the conclusion of this paper.

2.1 Sensor network – experimental setup

The investigation and test of the shadow imaging sensor network during robot movement was carried out in a lab with a 6-axis robot of type HORST 600. This robot has a repeatability of +/- 0.05 mm and a carry-capacity of 30 kg. The HORST 600 carries three LEDs on a tool holder model. One LED has red, one green and one ultraviolet (UV) light. The sensor network comprises the minimal configuration for measuring the 6D-tool pose, which consists of two sensors per LED colour, i.e. 6 shadow sensors S1…S6, see Fig. 1. The origin of the machine coordinate system is defined in sensor S1.

Fig. 1. Robot HORST 600 with 3 LEDs on a tool model and 2 shadow imaging sensors per LED fixed on a clamping frame.

A concept for the future integration of the measuring system is shown in Fig. 2 with two exemplary sensors.

The sensors should be mounted on a separate frame. Since the shadow sensors need line-of-sight to the LEDs on the tool holder, using a sufficiently long forming tool avoids occlusions of the LEDs.

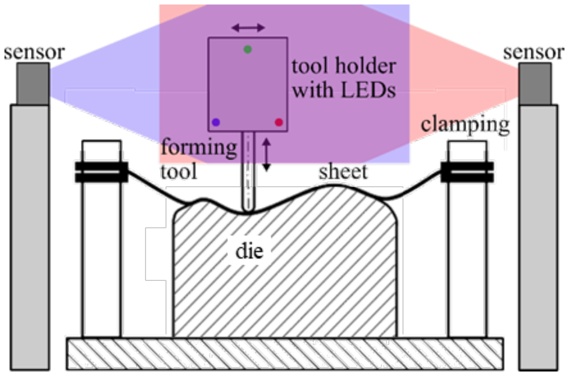

Fig. 2. Concept for the integration of the measuring system in the ISF setup.

The shadow imaging sensors of the measuring system mainly comprise a camera, housing, mask and colour filter, see Fig. 3 left, with a mask design as shown in Fig. 3 right.

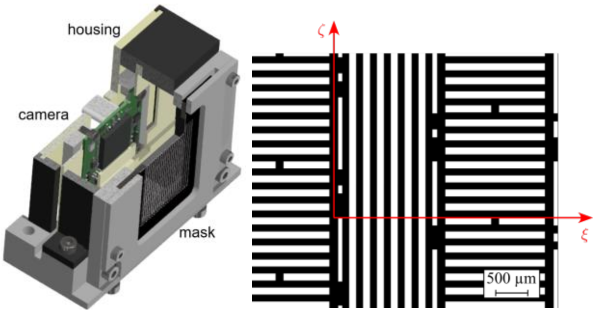

Fig. 3. Shadow sensor design (left) and mask design (right).

To test the motion tracking, a pyramid-shaped tool path was programmed, see Fig. 4. In the height of $z_{\mathrm{T,ref}} = 0$ mm, the centre of the tool holder model is vertically centred to the sensors. The tool path was traversed at the relatively low speed of 60 mm/min. With the current hardware, this enables one measurement every 0.68 s with 50 ms exposure time.

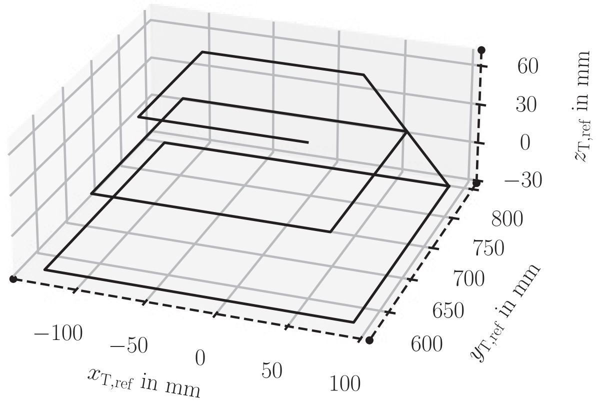

Fig. 4. Robot tool path for motion tracking test.

The general data processing for finding the LED position is divided into image processing and triangulation. The grids in the image are separated, the location of the stripes is determined from the light intensity profiles and the magnification between mask features and corresponding image features is calculated. Then, the mask position whose shadow hits the camera centre is computed. This mask position gives the direction from the sensor to the LED and triangulation of both sensors' results is performed via least squares optimization to obtain the LED position. Solving this requires an offline calibration measurement to determine the sensor positions and orientations and the distance between mask and camera.

2.2 NC-integration of shadow imaging sensor network

In the ISF process, real-time feedback and accurate position adjustments are critical for ensuring the accuracy and quality of the formed parts. Therefore, the coupling between the shadow sensor network responsible for pose measurement and the CNC controller of the robot (type Comau NJ-220) is crucial. The system architecture developed in this work enables seamless communication and real-time adjustments based on position feedback, thereby enhancing process precision.

The coupling between the shadow imaging sensor network and the robot's CNC control system is possible via the following system architecture:

1. *Shadow Imaging Sensor Network with Raspberry Pis:* Raspberry Pis process image data of optical sensors and the pose of the forming tool is calculated.
2. *Beckhoff TwinCAT 3 Soft-PLC:* Receives position data and transmits it over ProfinetDP to the Siemens 840D CNC controller. TwinCAT 3 is a widely used industrial automation software that provides high-performance control over automation processes.
3. *Dual-Port Profinet segment:* Shared memory space for both the soft-PLC and the CNC controller, enabling real-time data exchange.
4. *Siemens 840D CNC with RunMyRobot/Direct Control:* The CNC reads position data from the Profinet segment, calculates deviations, adjusts trajectory via synchronous actions and executes the corrected trajectory for accurate tool positioning.

The core of the pose measurement system consists of a shadow imaging sensor network that continuously monitors the tool pose relative to the workpiece. The sensor data is processed by a Raspberry Pi, which handles the image processing required to convert raw sensor signals into measured pose coordinates.

The Raspberry Pi's image processing results enable the calculation of the current tool pose within the workpiece frame. These pose coordinates are transmitted to the soft-PLC to provide the feedback necessary for the robot's motion adjustment.

The soft-PLC serves as the central communication hub between the sensor network and the robot's CNC controller. The soft-PLC allows for the real-time exchange of data between the shadow sensor network and the robot's control system.

To facilitate high-speed data transfer, the soft-PLC uses a ProfinetDP (Profinet Distributed Peripherals) communication protocol, which is an Ethernet-based standard designed for industrial automation. The communication takes place through a ProfinetDP coupler (type EL6631-0010), which links the Raspberry Pi, the soft-PLC, and the robot's CNC controller.

In this system, the ProfinetDP communication between the soft-PLC and CNC uses a dual-port Profinet segment, which is shared by both the soft-PLC and the CNC controller. The dual-port segment ensures that both the CNC and the soft-PLC can read and write data to the same memory space simultaneously. This setup allows the CNC controller to access the pose data measured by the shadow imaging sensors in real-time, ensuring synchronization between the sensors and the robot's movement commands.

In each interpolation cycle, the CNC controller uses so-called synchronous actions to read the current pose coordinates from the dual-port Profinet segment. These coordinates are the pose values measured by the shadow imaging sensors.

I. *Deviation vector calculation*: Upon reading the current pose coordinates, the CNC compares them to the internal command values for the Cartesian coordinates (as generated by the robot's path planning algorithm). The difference between the measured pose and the commanded pose is calculated as a deviation vector *d*. This vector represents the error or offset between the actual tool pose and the intended pose.

II. *Trajectory offset calculation:* The CNC controller calculates a trajectory offset vector (*offset* = -*d*) based on the deviation vector.

III. *Command Adjustment:* This offset is applied to the commanded pose values for each coordinate, effectively shifting the planned trajectory to correct for any pose deviations detected by the shadow imaging sensors. The updated trajectory, including the applied offset, is sent to the robot's motion control system. This ensures that the robot moves according to the corrected pose values, compensating for deviations in real-time.

The feedback loop enabled by the shadow imaging sensor network and the CNC controller is essential for maintaining the precision of the ISF process. By constantly comparing the measured pose (from the shadow sensors) to the commanded pose (from the robot's internal control system) and applying trajectory corrections, the system dynamically compensates for any errors that arise from robot or ISF. The required calibrations and validation tests are in preparation.

2.3 Vibration support – experimental setup

To quantify the influence of tool vibrations on the coefficient of friction, vibration-assisted tribometer tests (pin-on-disk, WAZAU) were conducted. A cylindrical pin with a half-dome-shaped tip (≙ forming tool) was pressed against a rotating test disk, representing the sheet material, under a defined normal force (Fig. 5, left). The coefficient of friction was calculated from the ratio of the normal force to the measured reaction torque. Ultrasonic vibrations were generated using a piezoelectric drilling tool operating at 23,6 kHz with an amplitude of 40 µm.

To evaluate the system and drive concepts for the ISF vibration unit and derive initial technical parameters, a mass-spring-damper model was developed (Fig. 5, right). It includes the self-adapting ISF vibration unit (piezo actuator, sonotrode and forming tool) and simplified boundary conditions such as the machine connection and workpiece coupling via forming force.

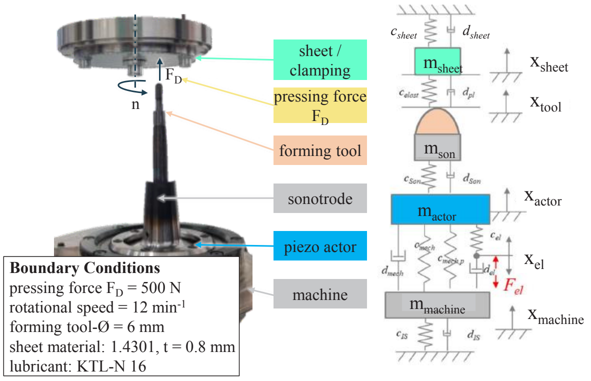

Fig. 5. Pin-on-disk setup with vibration assisted forming tool (left). Model of the ISF vibration unit with process position, workpiece and machine to adapt process parameters (right).

In both test setups, the forming tool was loaded with 500 N and a circular test track with a diameter of 40 mm was produced. The test comprised ten revolutions at 12 rpm. Drawing oil was used to lubricate the contact zone. Reference tests were carried out without vibration.

Funded by: Federal Ministry for Economic Affairs and Energy on the basis of a resolution of the German Bundestag (funding reference: DS200228). The IGF project no. 22860 BG of the Research Association for Measurement, Control and Systems Engineering (DFMRS) has been funded within the program for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry for Economic Affairs and Climate Action based on an enactment of the German Parliament.

3 Results and discussion

3.1 Sensor network – results and discussion

As a first step in assessing the possible robot accuracy enhancement by the shadow imaging sensor network, the static measurement uncertainty of the shadow imaging sensors is investigated. Multiple positions in the intended machining volume (Fig. 3) were measured and the tool pose was evaluated. Although the system is capable of measuring the tool pose, i. e. the position and orientation, te presented results focus on the three position components. The resulting systematic position errors are shown in Fig. 6. For this test, the movements were done on a Leitz PMM-F 30.20.7 coordinate measurement machine to provide a reference.

The static experiment shows a systematic error which is mostly below 0.1 mm but grows toward the outer edges of the sensors' field of view. This systematic error follows a clear trend, which enables a second calibration step to reduce the measurement uncertainty to the range of below 50 µm. Using this, the actual deviations of the robot in motion can be accessed via the shadow sensor network. Fig. 7 shows the measured tool path.

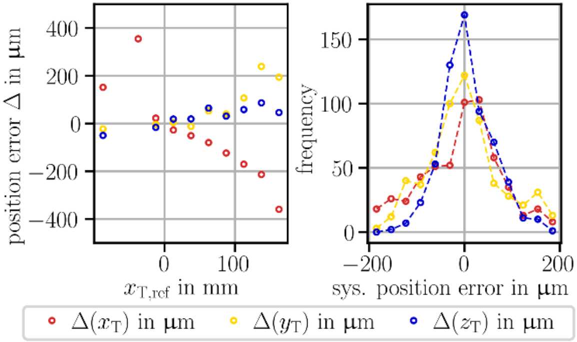

Fig. 6. Position measurement error of the shadow sensor network for a non-moving robot.

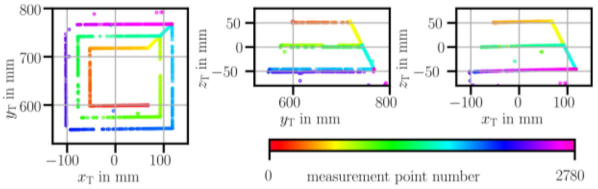

Fig. 7. Motion tracking using shadow imaging sensor network.

The measurement was done with a constant downward-facing tool orientation. Most of the positions on the path were correctly detected by the sensor network. The gaps and few outliers in Fig. 7 show, however, that the minimal setup allows for no redundancies and can lead to insufficient reliability for process control.

The deviations for two subsections of the path are shown enlarged in Fig. 8. The path measured by the sensor network reveals deviations up to about 0.1 mm, which can be compensated to well below 50 µm, a typical threshold for ISF parts. Further improvements to reliability as well as accuracy and measurement range are possible by expanding the sensor network with more shadow imaging sensors. The current hardware is not yet real-time capable but faster hardware, more efficient algorithms and parallelisation will allow pose updates in under 0.1 s, which is about double the camera exposure time. Since the ISF process is slow, a proper interpolation will then enable reliable, high-precision pose control.

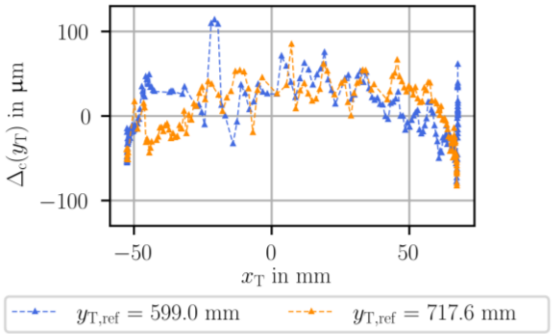

Fig. 8. Deviations of 2 tool sub-paths measured with the shadow imaging sensor network for a moving robot.

3.2 Vibration support – results and discussion

The analysis of friction coefficient over time curves in Fig. 9 across the evaluated frequency ranges clearly demonstrates a significant reduction in the friction coefficient through the application of high frequencies and sonotrode power. For instance, at a frequency of 23.6 kHz, the mean friction coefficient is reduced by approximately 72% (µ = 0.05) compared to the non-vibrational reference case (µ = 0.19).

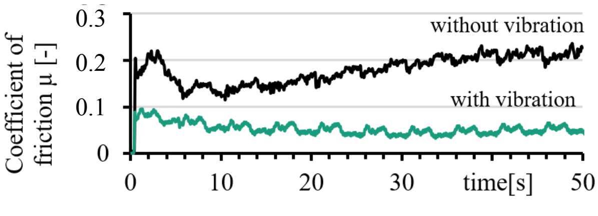

Fig. 9. Results of pin-on-disk tests.

The microscopic evaluation of the sheet surface after the test in Fig. 10 shows a clear widening of the friction marks under vibration by 30% from 1.7 mm to 2.2 mm. This enlarged friction track can be attributed to increased plasticization in the sheet thickness direction. This effect may be beneficial for incremental forming, as greater plasticization is likely to reduce the elastic component, thereby minimizing springback.

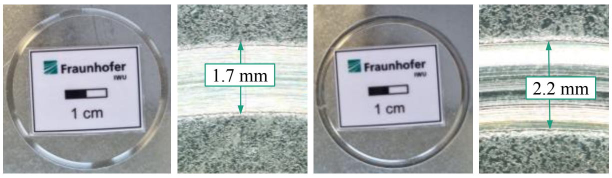

Fig. 10. Results of pin-on-disk tests. Comparison of wear marks on sheet metal: without (left) and with (right) vibration.

4 Conclusions

This study has achieved significant advances in the field of robot-based two-point incremental forming by systematically addressing the challenges associated with part accuracy and forming forces. The use of an advanced sensor network, analogous to a µGPS, has enabled accurate tracking of the tool pose, which can be used in future for a real-time measurement and control of the robot-driven tool motion. In our first experiments, the innovative use of shadow imaging sensor technology has allowed the robotic system's position data to be closely monitored, which will enable dynamic adjustments to be made during the forming process. In addition, the integration of ultrasonic vibration into the forming process has been shown to reduce forming forces by up to 70%, which improves forming conditions and mitigates issues related to tool wear and surface finish.

The presented advances provide a solid foundation for achieving higher accuracy classes in sheet metal forming, ultimately leading to the development of cost-effective manufacturing solutions that can achieve improved part precision. This makes robot-based technologies increasingly competitive and economically viable solutions for the modern manufacturing landscape.

In the future, research will concentrate on enhancing the integration of the sensor network and ultrasonic technology. This integration will enhance the adaptability and efficiency of robot-based TPIF systems. Comprehensive investigations into the underlying mechanisms governing ultrasonic assistance are imperative, as they may unveil novel parameters that can further enhance forming performance and material manipulation. Exploration of the scalability of these innovative techniques for broader industrial applications, particularly in the context of various material types and complex geometries, will be essential for maximizing the impact of these advancements. The integration of machine learning algorithms to predict and compensate for variances during the forming process will also be examined. Additionally, future research will focus on the impacts of machine innovations on incrementally formed components, with an emphasis on component evaluation and the optimization of machine technology for component quality. By pursuing these avenues, the objective is not only to elevate the quality and precision of produced components but also to solidify the role of robotic technologies in the rapidly evolving and increasingly automated landscape of advanced manufacturing. This approach is expected to result in the creation of affordable manufacturing means that achieve significantly improved component accuracies, thereby enhancing the overall competitiveness of the industry.

References

1. M. K. Agrawal, P. Singh, P. Mishra, R. K. Deb, K. A. Mohammed, S. Kumar, G. Kumar; Adv. Mater. Process. Technol., **10.2**, 506 (2024).
2. T. Schafer, R. D. Schraft, Rapid Prototyping J., **11.5**, 278 (2015).
3. C. Ye, J. Yang, H. Ding, Int. J. Mech. Sci., **233**, 107638 (2022).
4. M. Terlau, A. von Freyberg, A. Fischer, Int. J. Adv. Manuf. Technol., **136.2**, 761 (2025).
5. A. Harfoush, K. R. Haapala, A. Tabei, Procedia Manuf., **53**, 606 (2021).
6. F. Blaha, B. Langenecker, Naturwissenschaften, **42.20**, 556 (1955).
7. A. E. Tekkaya, P. Groche, B. L. Kinsey, Z. G. Wang, CIRP annals, **72.2**, 621 (2023).
8. Z. Chang, W. Peng, H. Long, J. Mater. Process. Technol., **336**, 118692 (2025).
9. H. Zu, X. Chen, Z. Chen, Z. Wang, X. Zhang, Measurement: Sensors, **18**, 100235 (2021).
10. Z. Li, S. Li, X. Luo, *Data-driven industrial robot arm calibration: a machine learning perspective*, in International Conference on Networking, Sensing and Control, ICNSC, 3-5 December, Xiamen, China (2021).
11. A. Nubiola, I. A. Boney, Robot. Comput. -Integr. Manuf., **29.1**, 236 (2013).
12. J. Belchior, M. Guillo, E. Courteille, P. Maurine, L. Leotoing, D. Guines, Robot. Comput. -Integr. Manuf., **29.4**, 58 (2013).
13. D. D. Störkle, D. Möllensiep, L. Thyssen, B. Kuhlenkötter, Procedia Manuf., **15**, 1164 (2018).
14. N. A. Sazonnikova, V. N. Ilyuhin, S. V. Surudin, N. N. Svinaryov, *Increasing of the industrial robot movement accuracy at the incremental forming process*, in International Conference on Dynamics and Vibroacoustics of Machines, DVM, 16-18 September, Samara, Russia, 1 (2020).
15. E. Grenet, P. Masa, E. Franzi, D. Hasler, Measurement system of a light source in space, U.S. Patent No. 9,103,661 (2015).
16. M. Vahdati, R. Mahdavinejad, S. Amini, Proc. Inst. Mech. Eng. B: J. Eng. Manuf., **231.6**, 971 (2015).
17. Y. Li, X. Chen, J. Sun, J. Li, G. Zhao, Procedia Eng., **207,** 777 (2017).
18. R. Cheng, N. Wiley, M. Short, X. Liu, A. Taub, Procedia Manuf., **34**, 186 (2019).
19. M. Yang, L. Bai, Y. Li, Q. Yuan, Adv. Mater. Sci. Eng., **1**, 8405438 (2019).
20. Z. Cheng, Y. Li, J. Li, F. Li und P. A. Meehan, J. Mater. Process. Technol., **299**, 117365 (2022).
21. R. Wang, W. Cheng, Y. Sun, H. Ge, W. Xu, J. Wang, J. Phys. Conf. Ser., **1678.1**, 012042 (2020).