Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 120 (2023) 1065–1070

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS '23, South Africa

Robot machining of thin-walled workpieces with automatically reconfigurable fixturing through feature analysis

Andreas Schütz[a,]*, Armin Lechler[a] , Alexander Verl[a] , Jürgen Fleischer[b]

[a] *Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, Seidenstrasse 36, 70174 Stuttgart, Germany*
[b] *Institute of Production Science (wbk), Karlsruhe Institute of Technology, Gotthard-Franz-Straße 5, 76131 Karlsruhe, Gremany*

* Corresponding author. Tel.:+49-711-685-82414. *E-mail address:* andreas.schuetz@isw.uni-stuttgart.de

Abstract

Machining of large scale thin-walled workpieces pose high requirements for fixturing because of large stiffness changes due to material removal. Automatically reconfigurable fixtures that allow in-process reconfiguration are a promising approach. In this paper, an efficient approach based on feature analysis is proposed for fixture reconfiguration planning. For this, material removal is simulated. At discrete points in time, feature analysis is performed and an approximated local stiffness map is calculated with weight functions derived from the features' parameterizations. Viable fixture configurations are then identified through root finding and validated through simulation in Ansys and experimentally with a fixture jig. In both validations, workpiece deformation for drilling operations could be reduced to an acceptable level enabling the implementation's future use in industrial application.

Keywords: industrial robot, robot machining, fixture, reconfigurable, flexible

1. Introduction

The use of industrial robots for machining applications is trending upwards. Their benefits include a good relation between working space and acquisition cost and flexible kinematics, allowing a great degree of freedom in orienting the tool, and are therefore capable of machining freeform workpieces [1,2]. Especially for thin workpieces and workpieces made out of low stiffness materials such as wood, composites or plastics, which all are characterized by comparatively low process forces while machining, industrial robots are able to manufacture products in quality comparable to conventional machine tools [3].

With mature technologies for machining prismatic and rotational workpieces with conventional machine tools, the use of machining robots is most promising for workpieces that cannot be easily manufactured using these machines. One type of workpieces to which this applies to is large scale thin-walled workpieces with curved or freeform surfaces. They occur in a variety of industries. Examples are car bodies in automotive industry, ship hulls in marine industry, airplane shells in aviation industry and covers and design objects in civil engineering and architecture. These workpieces are characterized by a low stiffness that further decreases while machining, which poses high requirements for fixturing.

1.1. Reconfigurable fixturing

In general, the goal of fixturing is avoidance of unwanted rigid body movement of the workpiece and preventing unwanted dynamic behavior such as deformation, vibrations or chatter under machining load and thus achieving high surface quality while complying with all geometric tolerances specified during part construction. Along with accessibility, stability and

10.1016/j.procir.2023.09.126

collision avoidance these make up the fixturing criterions that can be used to verify and validate successful fixturing [4].

Traditionally, modular systems, negative shapes or pin type fixtures are used. They all provide numerous contacts between fixture and workpiece under the assumption, this is sufficient for always ensuring fulfillment of all fixturing criterions. In reality, these types of fixtures have to compromise on the criterions, as for example always ensuring local rigidity while avoiding collision between fixture and tool for all machining steps poses a difficult problem.

Automatically reconfigurable fixtures allow the positioning of contact elements between fixture and workpiece before machining during initial setup [5] or while machining and are thus able to adapt to the manufacturing process while continuously complying with the fixturing criterions if planned correctly. Their flexible structure introduces challenges such as lower accuracy or stiffness compared to fixtures without actuators. Therefore, automatically fixtures are subject to research with the goal of improving construction, application [6], control [7] and planning algorithms.

While traditional fixtures are only adapted to a particular task during setup or in between manufacturing steps, the in-process reconfiguration of automatically reconfigurable fixtures introduces the problem of also fulfilling fixturing criterions during reconfiguration. Therefore, the planning algorithms discussed in the next section also have to be evaluated concerning their computational and thus time efficiency while dealing with geometry changes of the part during material removal.

1.2. Smart manufacturing systems

Automatically reconfigurable fixturing systems are an important part of smart manufacturing systems that try to achieve adaptability to new products and surrounding conditions and thus a high degree of efficiency. In combination with a robot for machining tasks, encapsulated cells can be constructed that operate autonomously based on simulative process planning and continuous data accumulation and use throughout the product's life cycle. These robot-based machining cells are suitable for integration in small craft enterprises, who are under economic pressure because larger companies enter their market segment of highly individualized products and can't rely on traditional automatization because of lack of needed domain knowledge.

1.3. System architecture

As first presented in [8], an automatically reconfigurable fixture has been developed at ISW. The system, which is depicted in Fig. 1, has 15 linear and one rotational axis. Altogether seven contact elements can be used for fixturing, with usually four used for positioning at the outer edge of the workpiece and three for gripping in the center. The latter three are repositioned during machining. The system is controlled via a Beckhoff TwinCAT PLC and CNC and is integrated with a Kuka KR500 robot equipped with a machining spindle.

To eliminate the influence of the automated system on investigations into the performance of fixture configurations, the jig pictured in Fig. 2 is used. With it, square plates up to $1\,m^2$ can be bolted down at the corner and workpiece deformation during machining is measured with a laser triangulation sensor.

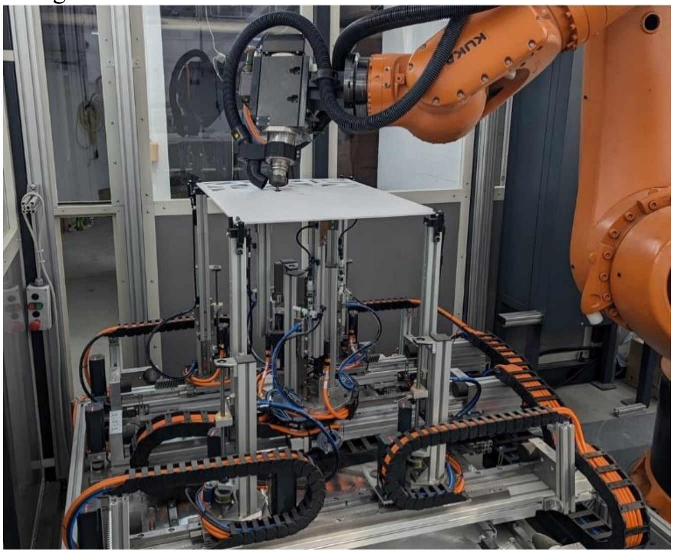

Fig. 1. Automatically reconfigurable fixture with Kuka KR500 at ISW

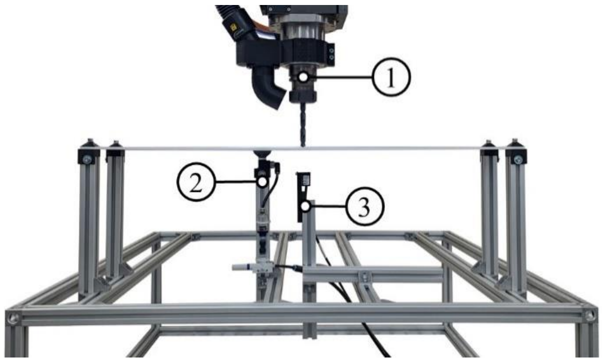

Fig. 2. Jig with machining robot (1), repositionable suction cup gripper (2) and laser triangulation sensor (3)

2. Planning algorithms for reconfigurable fixturing systems

Automatically reconfigurable fixturing systems can be reconfigured in-process. This allows for less contact elements, because only local fulfillment of the criterions is needed. But with this comes a more complex kinematic structure and thus higher demands are placed on the planning algorithms for reconfiguration.

According to [4], the process of determining a fixture configuration poses a multi-domain optimization problem in which a set of variables are sought, that achieve an objective while complying with constraints. The approach can be divided into the four consecutive steps problem description, fixture analysis, fixture synthesis and fixture verification.

During problem description, the initial optimization problem is defined. Usually, the variables with which the system can be manipulated are the degrees of freedom of the fixture in the form of movable axes or switchable grippers and are only depending on the fixture that is to be used. The objectives and constrains stem from the aforementioned fixture criterions and are mostly depending on the workpiece, with only collision interference being dependent on the fixture.

During analysis, a model is derived that relates the variables to objectives and constraints. This can be evaluated to determine successful configurations and contains kinematics, forces and deformation. In the synthesis step, previously derived models are used to identify the variables. Finally, the determined variables are verified to fulfill all posed conditions and the configuration determination is completed.

With the first step being highly dependent on the fixture system used in an application, most of the research in planning algorithms for fixtures is concerned with fixture analysis and synthesis. In the following chapter, the most relevant types of algorithms are presented with a focus on application in conjunction with automatically reconfigurable systems.

2.1. State of the art

While approaches only focusing on influencing the dynamic behavior of the workpiece such as introducing damping [9] or targeted excitation to avoid regenerative chatter [10] exist, most algorithms for fixture planning aim at minimizing workpiece deformation through placement of supports and grippers. The simplest approach is following the tool with a support, which is only possible for simple and continuous parts [11].

The conventional approach for fixturing of thin-walled workpieces is the transfer of rule sets aimed at preventing rigid body movement from prismatic workpieces such as the 3-2-1 principle as described in [12]. Case based reasoning models the behavior of experienced workers and makes the fixture setup dependent on the fulfillment of formulated conditions [13,14]. While both of these approaches yield good results for simple workpieces, they don't allow determination or approximation of the workpiece's deformation.

Continuum mechanics in the form of plate theory as a generalization of beam theory provides an analytic description of deformation for simple workpieces. Many different approaches exist [15], but none are suitable for application with workpieces with machined features.

Since no analytical solutions have been found, numerical algorithms in the form of finite element modelling (FEM) are widely used to calculate deformation. FEM discretizes the workpiece's geometry into smaller objects of given shape, which is also referred to as meshing, and solves a system of differential equations by fitting trial functions and solving a minimization problem. These algorithms are able to deliver great results, but require a high computational effort with the accuracy being dependent on fine meshing.

First uses of FEM for fixture planning consisted in using it in combination with rule sets [16]. The most popular use of FEM is in combination with genetic algorithms (GA) [17–21]. In these algorithms a fixture setup is assumed, and workpiece deformation is determined via FEM. During GA, fixture setup is changed and simulation is repeated. Depending on changes in workpiece deformation the procedure is repeated again until a termination condition is met. The Combination of FEM and GA has also been proven to work with reconfigurable fixturing [22,23], but is computationally very expensive. Taking into account the change in stiffness resulting from material removal, the algorithm has to be executed iteratively in small discretized time steps, further degrading its efficiency.

Although not present in fixturing algorithm research today, optimizations in FEM research such as adaptive meshing, adaptive time discretization or model reduction will improve the efficiency of FEM in combination with GA for reconfiguration planning. But the order of magnitude in efficiency optimization needed will likely not be achieved in near future.

An alternative approach that avoids costly simulation is the application of learning algorithms. Learning algorithms in the form of neural networks have only been used for simple geometries [24–27]. [28] uses response surface method.

A promising approach is the use of feature analysis, as is popular in the fields of computer aided manufacturing or machine vision. But so far, only few algorithms focusing on non-deformable workpieces were published [29,30].

2.2. Summary

Rule-based approaches work for most simple workpieces, but statements about performance for complex workpieces are hard to make. Algorithms based on FEM provide high quality results but are computationally expensive. Learning based procedures have so far been only used for simple workpieces in clearly confined scenarios. FEM and learning both avoid the use of further knowledge about the part beyond geometry. When geometry changes due to material removal while milling, the whole algorithm has to be computed again, resulting in constant computational effort for each time step in the material removal simulation. From this can be concluded, that there is a need for an analytical or simpler numerical algorithm that requires less computational effort and can be iteratively performed to consider material removal. This could either be an algorithm that itself is more efficient or uses results from previous iterations to increase efficiency.

Additionally, most algorithms converge to a singular solution, while often more are possible. In the planning of reconfiguration processes, duration of kinematic movements is relevant and should be considered when determining the next point of contact. From this one can conclude, that identification of multiple global solutions is to be preferred, because it enables better motion planning and control.

3. Feature-based approach

As previously described, finite element-based approaches present an accurate approach for determination of fixture reconfiguration at the cost of high computational effort. Algorithms in other domains such as computer vision are optimized for online use and therefore require less computation. The approach presented in this chapter is based on transferring optimized algorithms from different domains to the domain of fixture planning bunder the assumption, that the high accuracy in calculating quantitative deformations is not required and can be replaced with a qualitative optimization problem, which aims at finding sufficient fixture configurations instead of optimal ones. Qualitative hereby describes a model, that can provide relative order of system output, i. e. better or worse, for different inputs without quantifying the difference in outputs. The developed process chain consists of multiple steps, which are described in detail in the following sections. The presented approach tries to identify fixture configurations through feature extraction in geometries generated through material removal simulation and estimation of the influence of a feature on the workpiece's local stiffness based on the identified parameters. The same approach is followed for contact elements, with the difference that their parameters don't have to be identified because they are predetermined.

3.1. Material removal simulation

Fixture planning algorithms are based on a geometry description of the workpiece, but usually only models of raw material and the finished workpiece are available. While material removal simulation may be performed during CAM, no standardized interfaces for access are available. To get geometry information during machine, a material removal simulation has to be implemented based on previously described CAD-Models of the workpiece and the NC-code for the machine performing the machining operations. For the work presented here, such a simulation has been implemented. Depending on the specified movement speed of the machine, the tool is moved a discrete amount in space and collision detection between the geometry stored in a .stl-file and the tool, which is represented by an ideal cylinder, is performed. If a collision is detected, the geometry's surface is adapted by inserting new triangles into the contact border.

3.2. Feature identification

In machining of thin-walled plates, only finite discretely identifiable features exist: pockets, openings, surfaces, drilling holes, and edges. All of these features can be described by an associated parameter set each. In the following sections, drilling holes are used to exemplify the approach. For drilling hole features, their position and shape can be described by two parameters u and v of the parameterized surface description, which can be reduced to two cartesian coordinates x and y for flat workpieces, a vector **n** describing the orientation of the hole's central axis and the hole's diameter d_{h}. Identification of the feature can occur rule based on the discretized geometry description produced by material removal simulation, as it is characterized by a set of surfaces in recognizable orientation and layout.

3.3. Stiffness estimation

The main objective of fixturing in thin-walled workpieces is avoiding deformation through increasing local stiffness by providing support. The stiffness of thin-walled parts in the direction normal to its surface is orders of magnitude lower than in both directions in the surface plane. Thus, the local deformation behavior can be modelled as a underdamped harmonic oscillator, as has been presented in [7]. The system is excited by the force caused by the machining tool. This leads to the system in Fig. 3 for fixturing flexible workpieces with multiple contact elements.

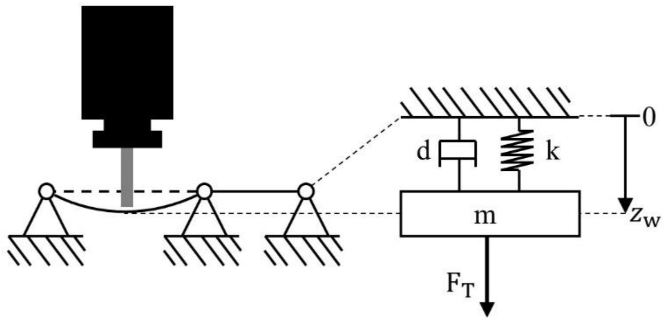

Fig.3. Diagram of mechanical system for local deformation behavior

The problem of fixture planning for reconfigurable systems with the goal of minimizing workpiece deformation at the current machining location can be reduced to the estimation of local workpiece stiffness k. The function that describes the influence of a feature or contact element on the workpiece's local stiffness is hereafter referred to as weight function W. To identify weight functions for drilled holes, simulations of a flat plate were performed in Ansys, whereby parameters of the hole were varied. Then the differences in local stiffness surrounding the hole compared to an unaltered plate were measured. Through fitting of functions, with the same parameters as used in feature description, to the measured differences, the weight functions for drill holes in the shape of

$$W(x,y,d_h,s_1,s_2) = s_2 * r(x,y,d_h,s_2) * e^{(-r(x,y,d_h,s_2))} \quad (1)$$

for $r(x,y,d_h,s_2) = d_h * s_2 * (x^2 + y^2)$ (2)

limited to $(x^2 + y^2) \leq 1$ (3)

with scaling factors s_1 and $s_2$were obtained.

Calculation of the local workpiece stiffness is executed with the help of what will hereafter will be referred to as a stiffness map. The stiffness map $M(u,v)$ is a function that assigns a normalized stiffness value to a coordinate on the workpiece's surface. In simple examples with flat surfaces this corresponds with the x and y axis of the global coordinate system. For curved parts, surface parametrization is necessary. Since normalized stiffness is calculated, no exact stiffness or deformation determination is possible. Fixture reconfiguration planning for automatically reconfigurable systems is more concerned with finding the possible optimum. While no strong separation is possible for all cases, ensuring that a sufficient configuration exists is assumed to be the responsibility of CAM processes.

First initialized with a value corresponding to the workpiece's blank's thickness, changes to the local stiffness are computed by superimposing weight functions of detected features or placed contact elements. Thereby has to be tracked, in which areas no material is left standing, to avoid wrong changes in local stiffness there later. The order of execution of the proposed algorithm's steps is pictured in Fig. 4. Based on the workpiece geometry generated in CAD and the manufacturing planning in CAM resulting in executable G-Code that can be executed by the robot, material removal simulation is performed. If a certain amount of mass is removed from the workpiece, feature detection is performed. Larger features that are currently being machined can always be represented as a combination of multiple smaller features. Newly detected features are added to the stiffness map with their weight functions. By reviewing posed fixturing criterions, the need for reconfiguration is determined. If a reconfiguration is needed, the optimization problem $max(k) = M(x,y)_{n-1} + W(d_F, x, y) * d_M$ with vector d_M as distance between origin of weight function W and current machining location is solved. The selection out of multiple equivalent solutions is performed in accordance with the fixture systems motion planning and not relevant here. If reconfiguration has to be changed, the stiffness map has to be updated. Since contact elements are temporary and machined features permanent, the future removal of weight functions of contact elements from the stiffness map has to be considered in implementation. In general, this approach is comparatively efficient and in iterative executions, the algorithm can reuse the stiffness map M_{n-1} of the last simulation step. Therefore, a complete simulation in every discrete timestep comparable to FEM approaches is avoided, which greatly benefits the algorithms overall efficiency.

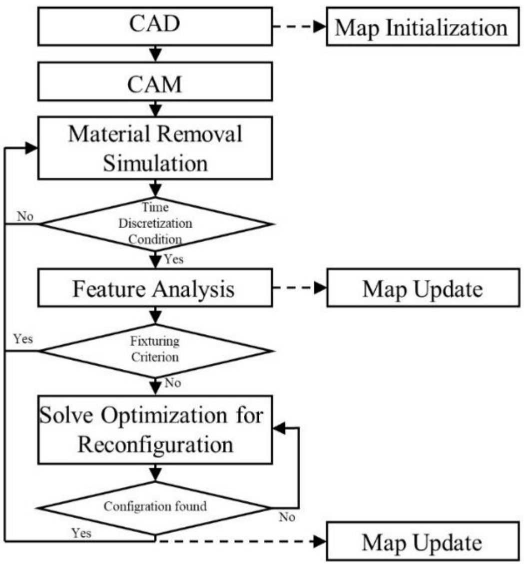

Fig. 4. Algorithm for fixture reconfiguration planning based on qualitative local stiffness estimation and stiffness maps

4. Validation

The approach is validated in finite element-based simulation of deformation under process load with the calculated fixture configuration in Ansys Mechanical through PyAnsys. The approach is also validated experimentally with the setup shown in Fig. 2. For both validations, the following scenario is chosen. In a plate of PVC with the dimensions of 900 x 200 x 5 mm that is mounted on a jig a pattern of 9 holes has to be drilled as depicted in Fig. 5. The soft material has been chosen to keep the process forces low to eliminate the influence of the jig's stiffness on the drilling process. For each hole that is to be drilled, the proposed algorithm is used to identify a viable fixture configuration, which in this case relates to the position of a single movable suction gripper with the 4 supports in the corner of the workpiece used for positioning remaining

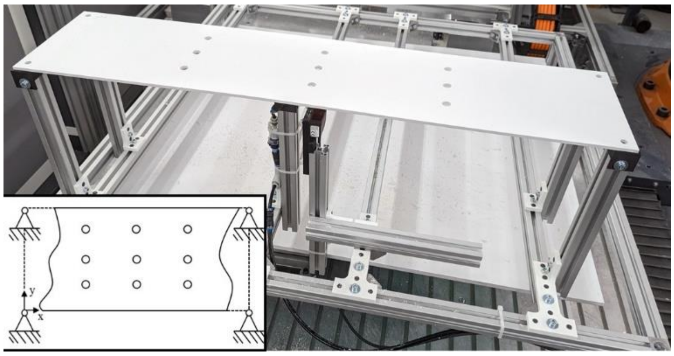

Fig. 5. Scenario for experimental and simulative validation for configuration planning algorithm with fixture jig an thin-walled PVC plate

unchanged. During simulation or real-world experiment, the deformation near the drilling location is measured as shown in Fig. 6, whereby the box indicates 25th to 75th percentiles, the whiskers result from max and min values and the median is highlighted in red. It can be clearly seen, that the deformation in experiments is larger than in simulation. This can be attributed to the non-ideal stiffness of the suction cup gripper used which is not considered in simulation. Overall, while still notably present, the deformation can be considered acceptable.

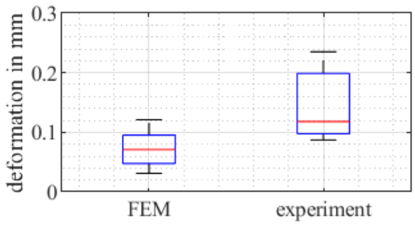

Fig. 6. Workpiece deformation in simulation and experiment

This is further supported, when the quality of resulting drill holes is considered as pictured in Fig. 7. The holes in the top row were achieved with the identified fixture configurations and show correct depth, smooth sidewalls, straight edges and an overall circular shape. Low quality results such as incorrect depth due to low stiffness, dominant tool marks in the walls, teared edges and oval hole shape resulting from insufficient fixturing as shown in the bottom row and obtained from earlier experiments were not present.

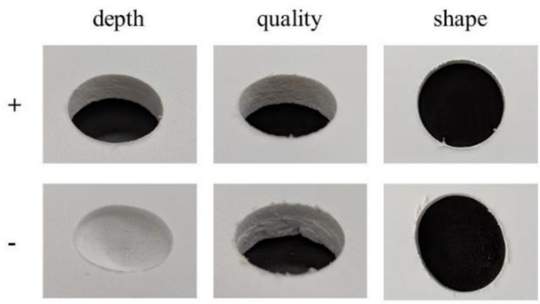

Fig. 7. Achieved quality and manufacturing defects for comparison

5. Conclusion and outlook

Available industrial robots possess a large and flexible workspace and are suitable for milling of workpieces made out of low stiffness materials and low workpiece thickness and therefore decreased process forces. The stiffness of these parts is further reduced when material is removed during milling, which poses difficult requirements for the fixturing.

Automatically reconfigurable fixturing systems allow online reconfiguration to always provide optimal support. For low stiffness thin-walled workpieces, FEM is most commonly used to optimize the fixture's position, elements and contact forces to minimize workpiece deformation or improve accuracy or process quality. While already computationally intensive, consideration of material removal further increases their required computational effort and prevents online use. To improve on this downside, this paper proposes a novel method for fixture setup identification and planning for automated in-process reconfiguration based on feature analysis and heuristic stiffness estimation for large-scale thin-walled workpieces while considering material removal. The results are validated in simulation and experimentally by performing workpiece deformation measurement during drilling with fixture configurations resulting from the proposed algorithm, which showed acceptable levels of deformation and good quality when optically inspected. This implicates, that the use of the implementation in an industrial setting with low available computational power as is the case in most small businesses is promising. To enable this, the approach has to be expanded to other features with corresponding machining operations such as pocket milling in future work. While rule-based feature detection and manual weight function calculation through curve fitting were appropriate for drilling holes, more complex algorithms from other fields such as feature extraction in machine vision or machine learning should be investigated for use. To eliminate the influence of kinematic accuracy and nonlinear behavior in movable axes, a dedicated jig has been used to validate fixture configurations. To reach the goal of application in industry, the proposed algorithm has to be used with an automated system. Since reconfiguration planning is dependent on the machine performing the milling, different machines have to be investigated in conjunction with automated fixturing systems for their ability to perform certain operations on thin-walled workpieces to advance these smart systems towards industrial applications in larger automated manufacturing units.

References

[1] Verl A, Valente A, Melkote S, Brecher C, Ozturk E, Tunc LT. Robots in machining. CIRP Annals 2019;68(2):799–822.

[2] Ji W, Wang L. Industrial robotic machining: a review. The International Journal of Advanced Manufacturing Technology 2019;103(1-4):1239–55.

[3] Menze C, Becker D, Stehle T, Möhring H-C, Helfesrieder N, Lechler A et al. Spanende Bearbeitung mit Industrierobotern und Bearbeitungszentren. WT Werkstattstechnik 2019;109(09):650–5.

[4] Bi ZM, Zhang WJ. Flexible fixture design and automation: Review, issues and future directions. International Journal of Production Research 2001;39(13):2867–94.

[5] Asada H, By AB. Kinematic Analysis of Workpart Fixturing for Flexible Assembly with Automatically Reconfigurable Fixtures. Journal of Robotics and Automation 1985;RA-1(2):86–94.

[6] Sagar K, Leonardo L de, Molfino R, Zielińska T, Zieliński C, Zlatanov D et al. The SwarmItFix Pilot. Procedia Manufacturing 2017;11:413–22.

[7] Schütz A, Lechler A, Verl A. Modelling for Control of Vacuum Grippers in automatically reconfigurable Fixturing Systems for thin-walled Workpieces. Procedia CIRP 2022;115:226–31.

[8] Schütz A, Helfesrieder N, Lechler A, Verl A. Automatisierte Werkstückfixierung. WT Werkstattstechnik 2020;110(01-02):80–5.

[9] Ma J, Zhang D, Wu B, Luo M, Chen B. Vibration suppression of thin-walled workpiece machining considering external damping properties based on magnetorheological fluids flexible fixture. Chinese Journal of Aeronautics 2016;29(4):1074–83.

[10] Moehring HC, Wiederkehr P, Gonzalo O, Kolar P. Intelligent Fixtures for the Manufacturing of Low Rigidity Components. Cham: Springer International Publishing; 2018.

[11] Fei J, Lin B, Xiao J, Ding M, Yan S, Zhang X et al. Investigation of moving fixture on deformation suppression during milling process of thin-walled structures. Journal of Manufacturing Processes 2018;32:403–11.

[12] Menassa RJ, DeVries WR. Locating Point Synthesis in Fixture Design. CIRP Annals 1989;38(1):165–9.

[13] Wang H, Rong Y. Case based reasoning method for computer aided welding fixture design. Computer-Aided Design 2008;40(12):1121–32.

[14] Sun SH, Chen JL. A Fixture Design System using Case-based Reasoning. Engineering Applications of Artificial Intelligence 1996;9(5).

[15] Thai H-T, Vo TP, Nguyen T-K, Kim S-E. A review of continuum mechanics models for size-dependent analysis of beams and plates. Composite Structures 2017;177:196–219.

[16] Cai W, Hu SJ, Yuan JX. Deformable Sheet Metal Fixturing: Principles, Algorithms, and Simulations. Journal of Manufacturing Science and Engineering 1996;118(3):318–24.

[17] Prabhaharan G, Padmanaban KP, Krishnakumar R. Machining fixture layout optimization using FEM and evolutionary techniques. The International Journal of Advanced Manufacturing Technology 2007;32(11-12).

[18] Krishnakumar K, Satyanarayana S, Melkote SN. Iterative Fixture Layout and Clamping Force Optimization Using the Genetic Algorithm. Journal of Manufacturing Science and Engineering 2002;124:119–25.

[19] Krishnakumar K, Melkote SN. Machining fixture layout optimization using the genetic algorithm. International Journal of Machine Tools and Manufacture 2000;40(4):579–98.

[20] Liao YG. A genetic algorithm-based fixture locating positions and clamping schemes optimization. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2003;217(8):1075–83.

[21] Ahmad Z, Sultan T, Asad M, Zoppi M, Molfino R. Fixture layout optimization for multi point respot welding of sheet metals. Journal of Mechanical Science and Technology 2018;32(4):1749–60.

[22] Xiong L, Molfino R, Zoppi M. Fixture layout optimization for flexible aerospace parts based on self-reconfigurable swarm intelligent fixture system. The International Journal of Advanced Manufacturing Technology 2013;66(9-12):1305–13.

[23] Ahmad Z, Zoppi M, Molfino R. Fixture Layoaut Optimization for Large Metal Sheets Using Genetic Algorithm. International Journal of Mechanical and Mechatronics Engineering 2013;7(7):1487–92.

[24] Lu C, Zhao H-W. Fixture layout optimization for deformable sheet metal workpiece. The International Journal of Advanced Manufacturing Technology 2015;78(1-4):85–98.

[25] Feng Q, Maier W, Stehle T, Möhring H-C. Optimization of a clamping concept based on machine learning. Production Engineering 2022;16(1):9–22.

[26] Qazani MRC, Parvaz H, Pedrammehr S. Optimization of fixture locating layout design using comprehensive optimized machine learning. The International Journal of Advanced Manufacturing Technology 2022.

[27] Selvakumar S, Arulshri KP, Padmanaban KP, Sasikumar KSK. Design and optimization of machining fixture layout using ANN and DOE. The International Journal of Advanced Manufacturing Technology 2013;65(9-12):1573–86.

[28] Yu K, Wang X. Modeling and optimization of welding fixtures for a high-speed train aluminum alloy sidewall based on the response surface method. The International Journal of Advanced Manufacturing Technology 2022;119(1-2):315–27.

[29] Dong X, DeVries WR, Wozny MJ. Feature-Based Reasoning in Fixture Design. CIRP Annals 1991;40(1):111–4.

[30] Zhou Y, Li Y, Wang W. A feature-based fixture design methodology for the manufacturing of aircraft structural parts. Robotics and Computer-Integrated Manufacturing 2011;27(6):986–93.