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Procedia Manufacturing 6 (2016) 17 – 24

Procedia MANUFACTURING

16th Machining Innovations Conference for Aerospace Industry - MIC 2016

Simulation based Planning of Machining Processes with Industrial Robots

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Abstract

Today, especially machining of large, integral constructed structural parts requires expensive machining centers. In contrast, modern industrial robots are characterized by flexible applications, large working spaces and low capital investment. Therefore, they provide high economical potential for machining applications in aerospace industry. However, their constructive characteristics like low stiffness and high sensitivity to vibrations lead to disadvantages compared with conventional machining centers. Due to this, extruded profiles were used as near to shape pre-products to reduce material removal rates within a new approach. Additionally, several methods for offline and online optimization of robot machining processes were developed and integrated in a new process chain for manufacturing of structural fuselage parts. Thereby, the conventional CAD-CAM process planning chain was extended with simulation based analyzation and optimization methods and a load-depending trajectory planning. The methods for offline process optimization within this novel process chain are presented in this paper.

Peer-review under responsibility of the NAMRI Scientific Committee

Keywords: robot machining; simulation based process planning; virtual machining

1. Introduction

Modern aircrafts are designed in order to maximize energy efficiency by low weight. Therefore, the structural components exhibit a minimal remaining material thickness as low as 1 to 2 mm and maximum rigidity. These complex shaped parts are up to 14 m long and typically manufactured from rolled aluminum plates. Today, such parts are

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Peer-review under responsibility of the NAMRI Scientific Committee
doi:10.1016/j.promfg.2016.11.003

machined on large machine centers with gantry shaped or hybrid - gantry in combination with a parallel kinematic head - design. The use of these machines is linked to high investments due to the large working space and the high requirements on stability. Regarding flexible applications and large working spaces, modern industrial robots might be an alternative. With low capital investment, robots provide high economical potential for machining applications. However, several effects, like gear backlash or chatter, have to be considered during process planning and machining due to characteristic disadvantages of industrial robots. Exemplary, fig. 1 shows the machined (a) and measured (b) surface with gear backlash induced shape errors.

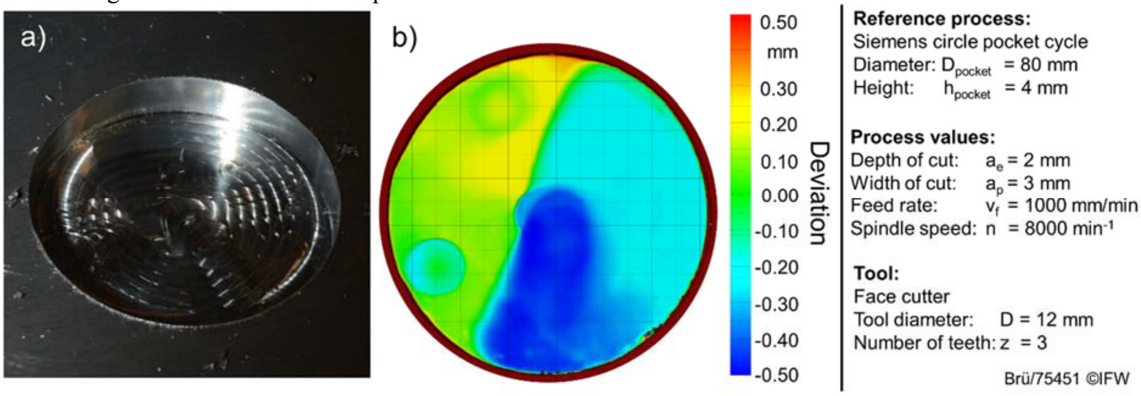

Fig. 1. Characteristic shape errors due to gear backlashes: a) machined surface, b) measured surface.

Challenging processes, like robot machining, requires consideration of technological interactions during process planning. Rehling developed a technological process simulation for the prediction of surface topologies due to process machine interactions like chatter [1]. Therefore the dexel method [2] was used for a time and path discrete analyzation of the cutting conditions. In the field of offline optimization of robot based machining processes, several approaches were presented. Abele et al. investigated the performance of industrial robots for machining applications by experiments and a stiffness model [3]. Bauer et al. analyzed the process machine interactions of robot structure and milling processes and optimized processes by using path manipulation [4]. Lehmann et al. used a similar approach for offline compensation based on calculated tool path deviations [5]. Cen et al. developed an online compensation method based on force sensing and an inverse force model for deviation detection of cutting conditions [6]. A major disadvantage of error based tool adaption is the lack of practical relevance for aerospace applications. Due to legal restrictions, machining processes have to be planned on the desired contour and certificated. In most cases, a later adaption of certificated processes is inadmissible. In addition, full integrated robot modules in the CAD-CAM process chain for aerospace applications are still missing.

Within the research project INNOFLEX novel AlCuLi-alloys and near-net-shape extruded profiles for integral structural parts were analyzed. Main advantages of near-net-shape profiles are the reduction of cutting volume and cutting forces compared to volume precision machining. As a result, the external load of robots is substantially reduced during machining. In combination with a simulation based planning, this can be the starting point to enable an industrial robot for machining applications in aerospace industry.

2. Approach

Aiming for increasing performance of robot based machining processes, the conventional CAD-CAM process planning chain was extended with simulation based analyzation and optimization methods (fig. 2): The developed planning system contains a technological process simulation for a discrete analyzation of the cutting conditions. On this basis, semi-empirical models are utilized for the calculation of process forces [7, 8]. The technological process simulation system is used to characterize and analyze the progress of the initially planned tool paths. Thereby, critical process states, for example peaks of process forces, rapid changes of cutting conditions or axial feed, are identified by knowledge based multi-criteria process analyzation. Critical process states are visualized and avoided by automated optimization routines like feed rate adaption or cut segmentation. In the next step the process simulation is coupled with a deflection model of the robot [9] and a model of gear backlashes to consider the interaction of process and manufacturing system. Based on the simulation, the production results are predicted, evaluated and optimized by tool path adaption or the specification of adapted robot postures.

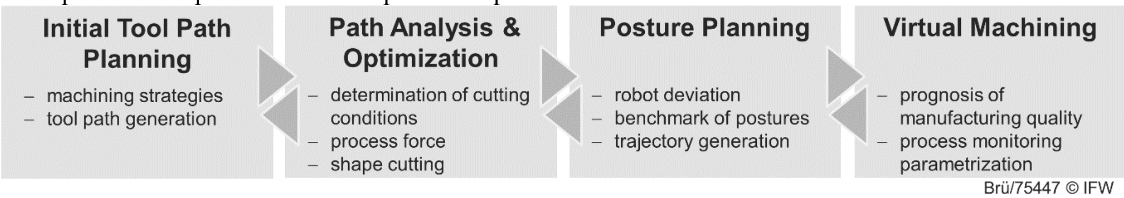

Fig. 2. Simulation based process planning for robot machining.

3. Simulation based tool path analysis and optimization

The initial planed tool path has an evident influence on the achievable manufacturing result. Fig. 3 shows four different surface topologies considering the gear backlash. Changing load direction of strategies zig-zag, helical and trochoidal milling (fig. 3b to d) result in inhomogeneous surfaces. As opposed to this, the homogeneous load conditions of zig strategy lead to smooth surfaces (fig. 3a).

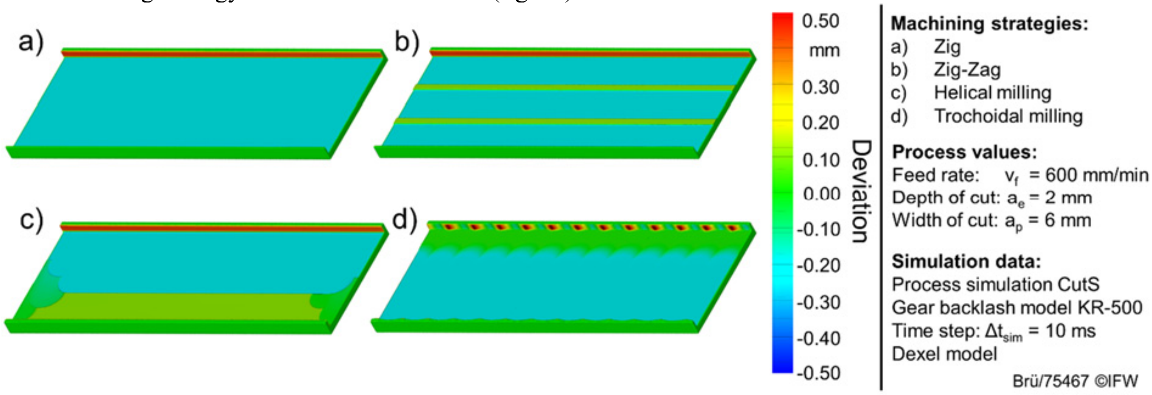

Fig. 3. Influence of machining strategies on surface topology due to gear backlash.

In addition to this, the analysis of the toolpath has the goal to detect and to avoid resulting manufacturing errors in an early process planning step. Due to this, a technological NC simulation developed by IFW named CutS [10] is used to evaluate the initially planned toolpaths. An extension of CutS aggregates continuously position-dependent data during the whole process simulation. The CAM generated tool paths are loaded into the controller model via the neutral formats CL-DATA (DIN 66215) or Standard NC Code (DIN 66025). An appropriate interpreter transforms the motion commands in movements of the tool relative to the work piece. Based on the dexel approach the cutting conditions between tool and workpiece are determined at each time step of the simulation. The knowledge about the current cutting conditions is used to derive geometrical and technological process conditions.

An essential part of the evaluation of machining processes is the prognosis of process forces, due to their main effect on the manufacturing result. The applied process forces model bases on the semi-empirical approach of Weilenmann [7]. This approach allows an efficient calculation of forces based on cutting conditions and a parametric description of the tool shape. Cutting edges and tool rotation are disregarded in the process simulation to decrease calculation time. For an approximate determination of the process force, coefficients are available in large numbers in literature [11]. In addition, coefficients can be specifically determined in experiments. Fig. 4 shows a comparison of the simulated and the real course of spindle torque for a single pocket operation in an exemplary application. Thereby, a common cutting force coefficient k_c = 780 N/mm² was used for machining aluminum alloy.

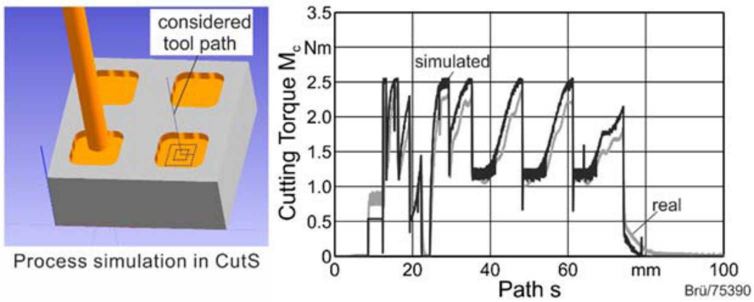

Fig. 4. Simulation of process simulation.

After the simulation, the process is evaluated based on the aggregated data. The different analysis routines use technological knowledge to evaluate the simulated process conditions. The evaluation is based on experimentally determined criteria, which were deposited in the form of mathematical rules and Boolean algebra in different analysis modules. The developed prototype includes an analysis regarding the occurring process forces, process stability, tool immersion behavior and possible structural changes. The basic operation of this analysis modules is exemplary visualized in fig. 5 by reference to a routine to avoid thermally induced structural changes, the so-called soft spots. An important advantage of this approach is that no extensive simulations of physical or metallurgical interactions are necessary. Instead, existing manufacturing knowledge can be used to parametrize rule based analysis functions. The realized routine for avoiding soft spots is based on knowledge of the project partner Premium Aerotec and experimental investigations showed in [12].

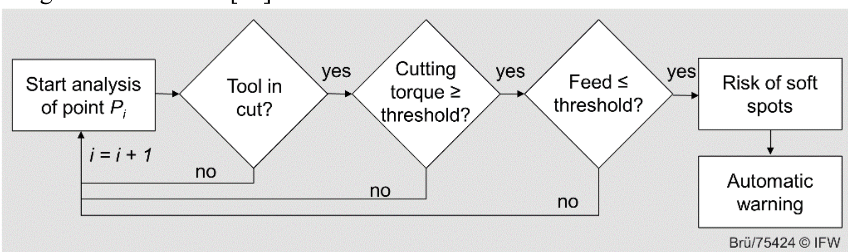

Fig. 5. Offline process analysis.

In addition to the workpiece related analysis of the toolpath, the behavior of the deployed manufacturing system is verified in further toolpath analyses. For example, the analysis routine detects process forces above a given threshold, which results in tool deviations which cannot be balanced by an online compensation [9] within the specified tolerances. In this case, a re-planning or adaption of toolpaths is necessary. The developed optimization routines base on a feed rate adaption or a segmentation of the affected cutting operation. Their use vary depending on the particular requirements. The feed rate adaption is used in the case of a small or local restricted transgressions of the threshold. The segmentation of cutting operations is used in cases in which a feed rate reduction would lead to an inefficient machining compared to operations with a reduced depth of cut a_p.

As a result of changing process conditions, stability behavior of the process can be worsened. These cases are identified by an automated analysis of the process stability on tool and machine specific stability cards (as described in [12]). In case of unaccomplished stability criteria, the user can adjust the affected cutting operation by an automated selection of valid cutting speed.

4. Automated load-optimized prepositioning

Due to the posture and load dependent misalignment of the robot, the positioning of the robot relative to the workpiece has a significant influence on the manufacturing result. Moreover, because of the complex system of equitation of robot kinematics, different valid postures can be used to achieve a path point. Each of these postures has different positioning errors under load. This is important for two aspects: On the one hand this interrelationship allows a load-optimized prepositioning. On the other hand a workload optimized trajectory influences the achievable manufacturing results.

Based on this, a method for the automated pre-positioning of workpiece and robot was developed. The built-up Broetje Automation manufacturing cell with an industrial robot Kuka KR-500 L340-2 uses an additional translational axis for guiding the robot. In addition, the cell has a flexible clamping system provided by J. Schmalz GmbH. This can vary the clamping position of the workpiece by using translational movable, modular vacuum clamps. Due to this, the manufacturing cell has two additional degrees of freedom. Semi-empiric determined accuracy maps describe the robot specific stiffness behavior for different load cases. By using the process data of the initial tool path characterization (compare chapter 3), the expected work load is known for every path point. The positioning of the robot relative to the workpiece is possible within the plane defined by the translational axis and the axes of the clamping system. The combination of accuracy maps and process data allows an automated selection of a process-specific, optimal clamping position of the workpiece. The described approach is schematically illustrated in fig. 6.

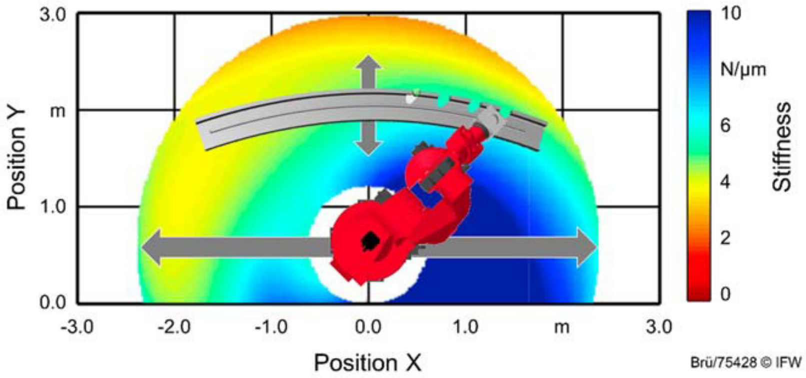

Fig. 6. Using accuracy maps for work piece and robot positioning.

5. Virtual machining

Objectives of the virtual machining are the determination of suitable robot postures, the forecast of the achievable production quality and the teachless parameterization of a process monitoring system. To use the robot models in different steps of planning, a modular approach was developed. This ensures a standardized cooperation of the models in the various planning modules.

5.1. Prediction of workload dependent positioning errors

The basic model for the deviation behavior of the robot is based on a Cartesian stiffness model. This is parameterized locally within the workspace by empirically determined stiffness values. For the simulation of occurring interactions between process forces, robot misalignment and the resulting tool displacement, the Cartesian stiffness model was coupled with the process model. In the first step of each time step, the cutting conditions are calculated for test purposes using the tool displacement of the last time step. These cutting conditions are used for an initial process force calculation. Afterwards, these forces are used within the stiffness model to forecast the resulting tool displacement. Subsequently, the difference between the assumed and the recently determined displacement are compared. In case of a mismatch of both displacement values, the cutting cycle is repeated with an adapted start value of the tool displacement. In the case of a difference smaller than a given threshold, the assumed displacement is used for the final modification of workpiece model in the current time step. For the consideration of robot posture depending influences like work load depending misalignments in the rotational axis of the robot, this basic method was enhanced by a robot misalignment model described in [9].

5.2. Prediction of gear backlash dependent positioning errors

Changing directions of rotation lead to alternating stresses in the gears of robot axes. These so called gear backlashes lead to incorrect positions of the involved axes and to positioning errors of the end effector. Due to changing strain conditions in the gears, the gear backlash is subject to a hysteresis effect. As shown in fig. 1, especially cutting operations with a large number of changes of rotation directions are affected by gear backlash. Aiming to characterize the gear backlash in the single robot axes, a numerically method for backlash identification was developed on the basis of experimentally determined data of laser trackers and recorded control data. The target positions of the tool center point (TCP) were determined by discrete time steps from the axis data of the control and forward kinematics of the robot. These target positions were compared with the measured tool path data of the laser tracker to calculate the deviation of the TCP. Subsequently, the corresponding axis values for the faulty TCP position were determined based on an inverse kinematics. These axis values were compared with the recorded target axis values to determine the misalignments in every single robot axis. The misalignment corresponds to the gear backlash. Fig. 7 exemplarily shows the extracted hysteresis effect for axis A5 of the used robot.

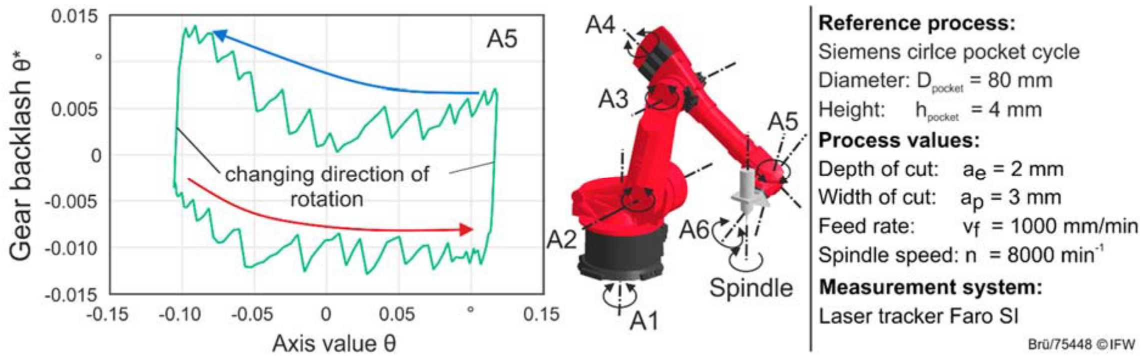

Fig. 7. Backlash in gear axis A5.

The gear backlash values of axes A1 to A6 are shown in tab. 1.

Table 1. Backlash characteristics of axes A1 to A6.

Axis	A1	A2	A3	A4	A5	A6
Lower limit	-0.012°	-0.004°	0.016°	-0.015°	-0.015°	-0.002°
Upper limit	0.006°	0.017°	-0.005°	0.007°	0.014°	0.004°

The determined backlash characteristics were used to parameterize a backlash model in process simulation. The backlash of each axis is assumed as the value of respective error axis additionally to the robot kinematics. The error axes have the same orientation as the respective robot axis. During the process simulation, the respective value of the gear backlash is determined at each time step depending on the current rotational motion and the accordingly error axis value. A comparison of experimentally determined and virtually determined component surface is shown in fig. 8.

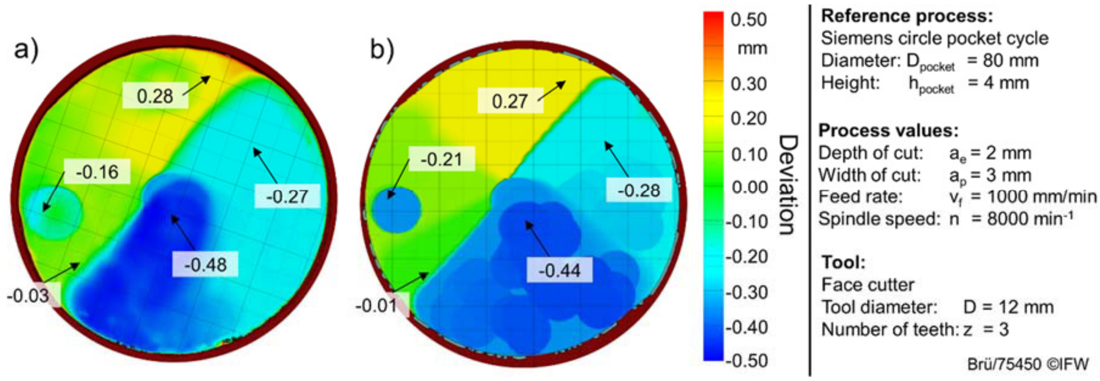

Fig. 8. Comparison of (a) real and (b) virtual machined pocket.

5.3. Automated process assessment

The described models for process machine interactions are used for an automated assessment of the planned machining processes. The main assessment criterion is the compliance of form and position tolerances. Therefore, the virtual machined workpiece model is compared with an integrated model of the target shape including valid tolerances. In the case of a violation of the given restrictions, the programmer is warned automatically by the planning system. The warning includes a detailed description of the process conditions during the affected cutting operation. In the case of a pass of the given restrictions, the aggregated information about the planed process are stored for later use in the case of occurring failures during ramp up.

5.4. Teachless parametrization of process monitoring system

Within the extended CAD-CAM process chain for robot machining, the approach of teachless parametrization of process monitoring systems [13] is used to shorten and optimize ramp up processes. Therefore, obtained process information from the path planning is utilized for configuring the process monitoring system without any teaching processes. As described in chapter 3, information about the process like cutting torque, process forces or cutting conditions is determined by a technological NC simulation. These information was augmented in all steps of the planning process chain. For the determination of process limits, the course of the predicted cutting torque is automated normalized and split into sixteen levels. All neighbored path point with the same level are summarized to one process segment.

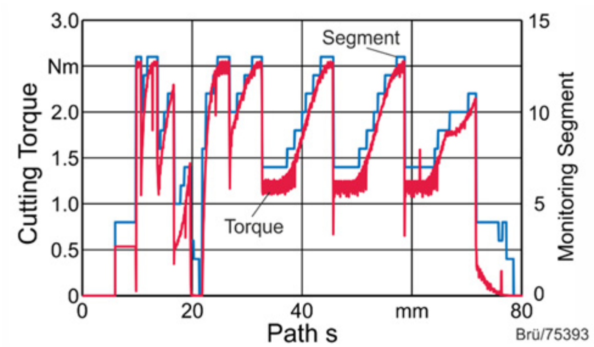

Fig. 9. Process segmentation for parametrization of process monitoring system.

As shown in fig. 9, these segments serve as a qualitative description of the process course for the teachless parameterization of monitoring limits in the process monitoring system. The cutting torque is used because of its adequate correlation with the monitored spindle torque. During monitoring, the expected spindle torque and the derived limits are calculated on the basis of the segments and the measured spindle torque. For the parametrization of the used process monitoring system Artis Genior Modular OA, the segments are exported via a defined XML format. The teachless parametrization enables the process monitoring system to detect variances from the predicted process. Variances can be issued for example by excessively tool wear or a broken tool. Thereby the monitoring system is able to stop the process and avoid further damages of the machined part or the manufacturing system.

6. Conclusion and outlook

This paper presented an approach for an enhanced CAD-CAM process chain for robot machining processes based on several simulation models. On the one hand, the simulation results are used in the different steps of process planning to detect and avoid occurring errors as early as possible. On the other hand, the simulation results are aggregated for an efficient reuse in following planning steps. In the final step, the aggregated process information are used for the teachless parametrization of a process monitoring system.

This example shows the necessity for an augmentation of the process planning with technological knowledge about the process, the manufacturing system behavior and their interactions. Simultaneously, the opportunities of a classical offline process planning are restricted concerning current state information like tool wear, clamping situation and thermal behavior. In the case of robot machining, effects like gear backlash can be predicted and compensated offline. Nevertheless this is connected to a resulting loss of the boundlessness regarding the versatility of the process. Therefore, the borders between process planning systems and manufacturing systems have to be dissipated in the future.

Acknowledgements

This work has been funded by the Ministry of Economics, Labour and Transport of Lower Saxony within the project “Innoflex” (ZW3-80134969). The authors would like to thank the federal state of Lower Saxony for their financial of this project.

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