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Procedia CIRP 46 (2016) 165 – 168

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7th HPC 2016 – CIRP Conference on High Performance Cutting

Advanced Simulation-based Design of High Performance Machining Processes

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Abstract

The development of high performance machining processes is a key aspect to achieve higher productivity, efficiency and performance in modern production systems. In order to reduce the corresponding effort and costs, simulation systems are one possibility to support the design and the optimization of manufacturing processes. In this article, three different application examples with respect to milling, grinding and deep-hole drilling operations are presented. In this context, both finite-element and geometric-kinematic simulation approaches are applied to model the different challenging issues of the corresponding machining process.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz

Keywords: High Performance Cutting; Simulation; Milling; Chatter; Deep hole drilling; Thermal error; Straightness; Distortion correction; Grinding; Temperature; Thermal effects;

1. Introduction

High performance cutting enables energy and resource efficient machining [1]. Therefore, this technique is applied in different sectors of the manufacturing industry and even for machining of advanced aerospace alloys and composite materials [2, 3]. A shorter product lifecycle necessitates also higher flexibility of the production systems. Thereby, simulations are used to model the entire product and production lifecycle with the objective to reduce the corresponding effort and costs [4]. Regarding the design of machining processes, different simulation methods are established to predict specific tool-, machine- and workpiece-related characteristics. Geometric-kinematic approaches are often used to simulate milling processes, calculating the material removal by the tool-workpiece-engagement along the NC-path. For the discretization of the workpiece and the tool, different modeling techniques, such as constructive solid geometry (CSG), dexel and wire- or point-based methods, can be used [5]. These simulations allow a detailed representation of the contact situation and the corresponding undeformed chip thickness. Based on empiric and analytic models, the cutting force and its components can be estimated. Combining these calculations with an appropriate modeling of the system dynamics, the occuring of chatter vibrations and the resulting surface topography of the machined workpiece can be predicted [5]. In grinding operations, the same fundamental geometric-kinematic approach can be applied on the macro-scale to analyse complex contact conditions and forces. Furthermore, the grinding tool topography can be considered on the microscopic level to allow the simulation of the multiple single grain engagements within the contact zone [6].

Modeling of machining operations is often performed using finite-element (FE) methods. On the one hand, this technique allows the macroscopic simulation of tool and workpiece, regarding mechanical, thermal or dynamic effects [7, 8, 9]. On the other hand, the main research focus is represented by FE-analysis of chip formation on the microscopic level. Thereby, a local model of the material separation in the working zone is used to predict forces, temperatures or surface integrity [8, 10].

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Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz
doi:10.1016/j.procir.2016.03.167

2. Simulation-based design of milling processes in series production of cylinder heads

Today's trial-based process design during the planning and start-up phase of series production cannot always be transfered to the final manufacturing system, since the boundary conditions in these stages, e.g. workpieces, tools, and machines, can differ substantially from each other. At the start of series production, this can cause unwanted delays, as the determined process layout may have to be adapted. Additional experiments in the start-up stage imply an increase in costs and resources. To avoid this, new designing approaches, particularly of innovative processes, have to be developed and applied.

Using the simulation tool, developed by the Institute of Machining Technology at the TU Dortmund University, the process design can be supported from the beginning. Based on a NC program, cutting force parameters, a structural-dynamic description of the tool, tool holder and machine system as well as the tool geometry, the simulation system calculates the cutting forces and vibration of the tool center point. Thus, the stability of a process can be assessed independently of existing machine tools [5].

In the machining process of cylinder heads at Daimler AG, the inlet ports are milled through the bore of the intake valves to generate a tumble air flow. This operation requires long cantilevered milling tools with a small tool diameter. In addition to casting tolerances, this can cause chatter vibrations because of varying cutting conditions and unsuitable process parameters. To ensure the manufacturability of this feature, the simulation tool is used in an early stage of the product development process. To examine the process stability, a parameterized blank model is required, representing the preliminary casting process with its corresponding tolerances.

For this purpose, a NC program of the blank part in nominal position is generated by a CAM system. Following, the blank part is transferred in the simulation environment, as shown in Fig. 1. The tolerances of the preliminary processes are modelled by manipulation of the generated NC program, e.g. by rotation and translation of the NC points, to simulate their influence on the machining process under examination.

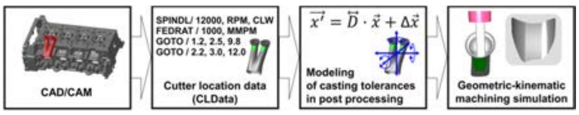

Fig. 1: Building a parameterized blank part model considering the casting tolerances by manipulation of the NC paths.

The comparison of simulated and machined surfaces for different translational casting tolerances of l = ±0.9 mm is shown in Fig. 2. These values are achievable for sand casting of parts with dimensions of l > 450 mm [11]. Test workpieces with defined casting tolerances were used to verify the simulation approach resulting in a good agreement. Furthermore, the simulation could predict the actual cutting forces measured in tests as well.

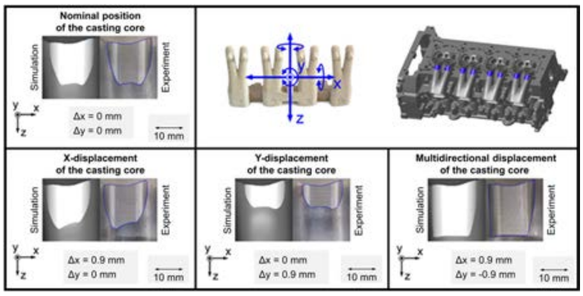

Fig. 2: Machined surfaces in the simulation (left) and on real parts (right).

3. Hybrid multi-scale modeling of high speed internal traverse grinding

Internal traverse grinding (ITG) is a finish operation for bores in different fields of the industry, e.g. gears or bearings. In order to achieve high material removal rates comparable to hard turning processes, the peel technique of ITG using electroplated grinding wheels can be applied under high speed conditions [12]. In this case, the grinding wheel is divided in a conical roughing zone and a cylindrical finishing zone. In contrast to internal plunge grinding, the ITG tools have small width of the grinding wheel, resulting in a compact form of the contact zone and locally concentrated thermal as well as mechanical loads onto the workpiece. This can cause thermally induced machining errors of the workpiece, such as form deviations or alterations of the surface layer.

To estimate the global thermal loads onto the workpiece, normally, FE models based on the moving heat source theory can be used [6]. In order to reduce the calculation time, only one volume segment is modeled in this study. The detailed simulation setup and procedure are described in [13]. The amount of the heat input into the workpiece is calibrated according to adjustment between measured and simulated maximal temperatures. In the right part of Fig. 3, a comparison of measured and simulated temperature curves after calibration is shown. Applying this FE simulation, the thermal load onto the workpiece can be estimated related to the macro-scale process parameters, e.g. the axial feed. Varying this parameter, the simulated temperatures within the contact zone rises by the larger axial feed according to the material removal rate, which is three times higher at these process conditions.

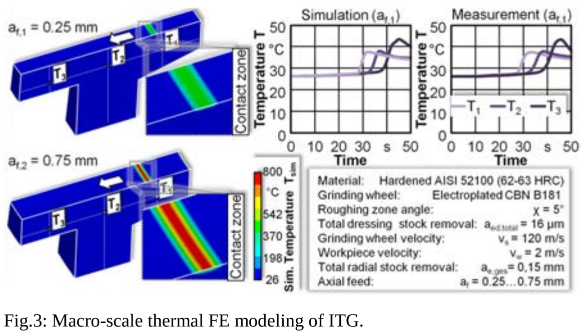

Fig.3: Macro-scale thermal FE modeling of ITG.