Prod. Eng. Res. Devel. (2009) 3:111–120
DOI 10.1007/s11740-008-0137-x

MACHINE TOOL

Modelling and simulation of process: machine interaction in grinding

J. C. Aurich · D. Biermann · H. Blum · C. Brecher · C. Carstensen · B. Denkena · F. Klocke · M. Kröger · P. Steinmann · K. Weinert

Received: 28 July 2008 / Accepted: 7 October 2008 / Published online: 15 November 2008

Abstract This article presents an overview of current simulation methods describing the interaction of grinding process and grinding machine structure, e.g., vibrations, deflections, or thermal deformations. Innovative process models which describe the effects of the grinding wheel–workpiece interaction inside the contact zone are shown in detail. Furthermore, simulation models representing the static and dynamic behaviour of a grinding machine and its components are discussed. Machine tool components with a high influence on the process results are modelled more detailed than those with low influence. The key issue of the paper is the coupling of process and machine tool models for

J. C. Aurich
Institute for Manufacturing Technology and Production Systems,
University of Kaiserslautern, P.O. Box 3049,
67653 Kaiserslautern, Germany
e-mail: aurich@mv.uni-kl.de
URL: http://www.uni-kl.de/FBK

D. Biermann (✉) · K. Weinert
Institute of Machining Technology,
Dortmund University of Technology,
Baroper Str. 301, 44227 Dortmund, Germany
e-mail: biermann@isf.de
URL: http://www.isf.de

K. Weinert
e-mail: weinert@isf.de

H. Blum
Institute of Applied Mathematics,
Dortmund University of Technology,
Vogelpothsweg 87, 44227 Dortmund, Germany
e-mail: heribert.blum@mathematik.uni-dortmund.de
URL: http://www.mathematik.uni-dortmund.de/lsx

C. Brecher · F. Klocke
Laboratory for Machine Tools and Production Engineering,
RWTH Aachen University, Steinbachstr. 19,
52074 Aachen, Germany
e-mail: c.brecher@wzl.rwth-aachen.de
URL: http://www.wzl.rwth-aachen.de

F. Klocke
e-mail: f.klocke@wzl.rwth-aachen.de

C. Carstensen
Department of Mathematics, Humboldt University Berlin,
Unter den Linden 6, 10099 Berlin, Germany
e-mail: cc@math.hu-berlin.de
URL: http://www.math.hu-berlin.de

B. Denkena
Institute of Production Engineering and Machine Tools,
Leibniz Universität Hannover, An der Universität 2,
30823 Garbsen, Germany
e-mail: Denkena@fw.uni-hannover.de
URL: http://www.ifw.uni-hannover.de

M. Kröger
Institute of Machine Elements, Design and Production,
TU Bergakademie Freiberg, Lampadiusstraße 4,
09596 Freiberg, Germany
e-mail: kroeger@imkf.tu-freiberg.de
URL: http://www.imkf.tu-freiberg.de

P. Steinmann
Chair of Applied Mechanics,
University of Erlangen-Nuremberg, Egerlandstraße 5,
91058 Erlangen, Germany
e-mail: paul.steinmann@ltm.uni-erlangen.de
URL: http://www.ltm.uni-erlangen.de

predicting the interactions of process and machine. Several coupling methods are introduced and the improvements of the simulation results are documented. On the basis of the presented simulation approaches, grinding processes and machines can be designed more effectively resulting in higher workpiece quality and process stability.

Keywords Process machine interaction · Grinding · Modelling · Simulation

1 Introduction

High quality and high value parts are usually produced in small lot sizes. Due to the high value of the parts, reject parts are not acceptable. However, the number of costly prototypes for identifying reliable process parameters and tool paths has to be reduced too. Especially grinding processes, which are applied as one of the last steps in the process chain, have to be focused since a process error during the finishing operations usually leads to high extra costs. Extensive experimental studies for finding optimal process parameters are not practicable. Therefore, very conservative process parameters accounting for long machining times are normally chosen. An application of simulation methods which predict the process behaviour and results during the planning phase would facilitate the selection of process parameters and increase productivity.

In the past, many approaches for modelling and simulation of grinding processes were developed and applied to gain detailed process knowledge. These approaches were mostly focused on grinding wheel - workpiece interaction. A comprehensive summary of the state of the art in simulation of grinding has been given by [1, 2]. Most of the models are only valid for a specific combination of grinding wheel, workpiece material, and grinding machine system. In order to increase the simulation quality, the effect of the machine tool behaviour during the grinding process has to be modelled as well. Vibrations and deformations of the machine structure caused by the process forces can be determined, which leads to a better predictability of resulting workpiece geometries and process stability. Strategies can be derived to reduce geometry as well as thermo mechanical errors by process parameters and/or tool path optimization, which are individually adapted to the machine.

This article focuses on modelling of processes and machines for different grinding kinematics. High-performance face grinding, pendulum and speed stroke grinding, as well as tool grinding, and NC-shape grinding are discussed as examples. The aim is an exact modelling of the grinding processes, the surrounding machine structures, and the interaction effects. In Sects. 2 and 3, several methods to model both, the grinding process, and the machine structure are presented. In order to simulate interaction effects, process and machine models have to be coupled. Different coupling strategies are discussed in Sect. 4.

2 Process models

A process model for grinding describes the complex relationship between process and machine parameters, and work results. The interaction is modelled by prediction of grinding forces, temperatures, grinding energies, surface integrity etc., depending on the process. Multiple approaches for building up a process model are presented in [1]. These include fundamental approaches as well as kinematic models, finite element method (FEM), molecular dynamics, physical and empirical, artificial neural nets, and rule based models.

This chapter focuses on the prediction of process forces occurring during grinding as an input value for a machine model in order to describe the interaction between the process and the machine structure. Due to the large number of abrasive grains with an unknown geometry which varies with time, grinding is a complex material removal operation [3].

The large number of input variables complicates the development of a universal model [4]. Due to different contact conditions, several models have been developed accounting for different grinding operations.

Kinematic-geometrical simulations are the basis of the presented process models. Therefore, the penetration between grinding wheel and workpiece is considered. Furthermore, these simulations can be distinguished between microscopic and macroscopic approaches which are described below. Their complexity and accuracy depend on the chosen modelling approach and the grinding process kinematics [1].

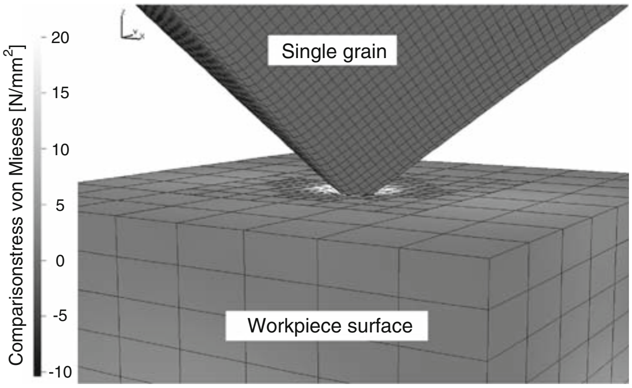


Fig. 1 Stresses in workpiece surface simulated by FEM [5]

2.1 Microscopic approaches

In microscopic approaches, the components participating in material machining are described in detail. In one approach, the grinding wheel consists of a detailed description of the complex 3D shape of each single grain and its randomly distributed position and orientation on the wheel, based on statistic functions determined by detailed statistical analyses of grinding wheel topographies [2]. Other approaches measure the wheel's topography and use this data for detailed modelling.

A different microscopic approach is shown in Fig. 1. A 3D FEM simulation model, showing the occurring stresses during a single grain penetration, is used. The simulation can be extended by considering multiple statistically distributed grains to represent grains on certain paths. The computed stresses of the grains are used to calculate the process forces.

Based on the knowledge of the grinding wheel topography in combination with the process kinematics it is possible to simulate the machined material by each grain using a 3D FEM.

Another approach is presented in Fig. 2a. It shows an ideal penetration of single grains and the workpiece surface based on the process kinematic and the assumption of ideal chip formation. Possible parameters to characterise the undeformed chips of a single grain penetration are shown in Fig. 2b. Single grains are modelled by ideal octahedrons, cuboids, tetrahedrons and ellipsoids, randomized by additional planes in different orientations to generate a complex shape [6].

The knowledge of the machined material and the accumulated chip cross sections leads to a calculation of occurring forces using a Kienzle equation [7], which is adapted for grinding processes. Due to the permanently changing contact conditions, especially during NC-shape grinding and tool grinding processes, the allocation of the effective grinding force can be included.

Some experimentally determined and simulated forces with the associated resulting surfaces are shown in Fig. 3. The experimentally determined process specific grinding force $k_{c,sim}$ relates the chip cross section to the grinding forces. The simulation leads to a good approximation of occurring forces. Taking different grinding wheel topographies, i.e. grain distribution and grain size, into account, a prediction of the workpiece surface can be accomplished.

2.2 Macroscopic approaches

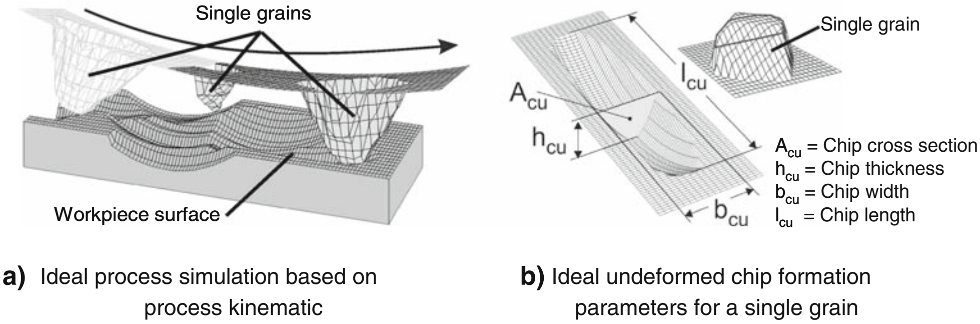
Macroscopic approaches describe the penetration of the workpiece by the shape of the grinding wheel without detailed specifications of the wheel's topography. Figure 4 shows a 2D approach to calculate the machined material using the chip longitudinal section depending on the cutting depth, the workpiece velocity, the chosen time step and the position of the grinding wheel. Thus the currently machined material is taken into consideration which is important for processes with rapidly changing grinding forces, e.g. during run-in or run-out phase in pendulum and speed stroke grinding.

Based on an empirical grinding force model, the process forces can also be determined using a 3D kinematic-geometrical simulation [10]. An adapted Kienzle equation relates the machined material to the occurring forces. Therefore, a factor for the specific grinding force ratio is necessary, which has to be evaluated by empirical data. The empirical data is generated by experiments taking material properties and tribology effects into account. In the kinematic-geometrical simulation, the workpiece surfaces can be described by dexel models. A dexel model is applied on a NC-shape grinding process in [11, 12]. Thereby, a local distribution of the contact stresses can be calculated by a macroscopic FEM simulation.

3 Machine models

The grinding process and the machine structure interact with each other [1]. For an exact simulation of these influences, the machine structure has to be modelled accurately [13, 14]. Therefore the machine model has to be able to respond to excitations coming from the grinding process and to create

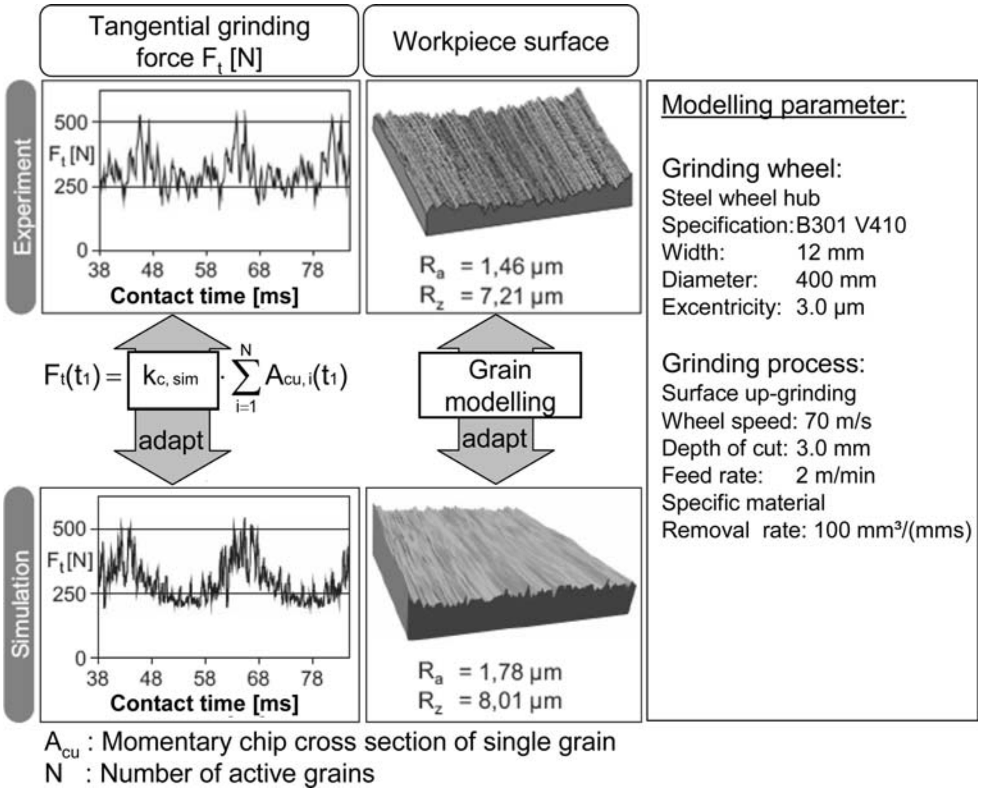
Fig. 2 Workpiece penetration [6]



a) Ideal process simulation based on process kinematic

b) Ideal undeformed chip formation parameters for a single grain

Fig. 3 Comparison of measured and simulated process results [8]



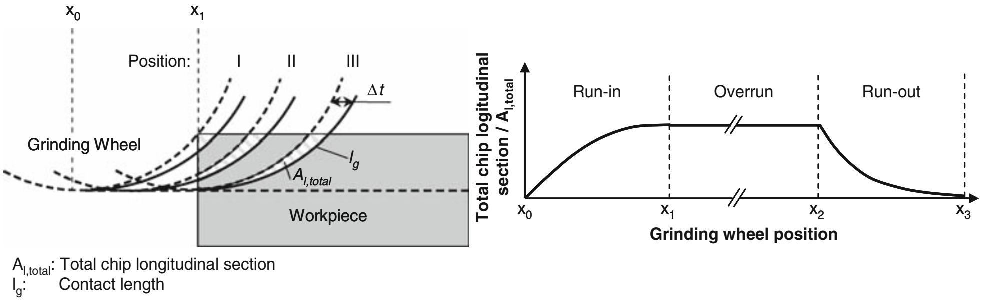


Fig. 4 Change of chip longitudinal section during face grinding [9]

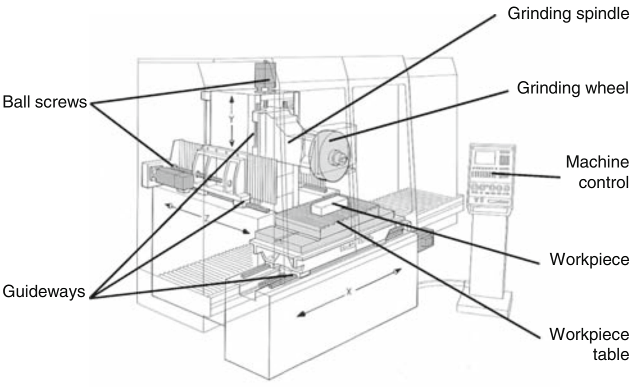


Fig. 5 Structure of a grinding machine [15]

an output which again has an influence on the calculated grinding process. Furthermore, the machine model should be built up as simple as possible to enable an efficient exploitation of the simulation results. Thus, simplifications of the model, which depend strongly on the considered grinding process, are required. For error estimation, the machine models are parameterized by experimental investigations, like modal analysis or measurements of the damping behaviour of special machine parts, in general. An exemplary grinding machine, which is represented by a machine model below, is illustrated in Fig. 5.

In this section, different possibilities to model a grinding machine are presented. Thereby, it has to be distinguished if the complete machine is modelled in a full machine model or only special parts of the machine

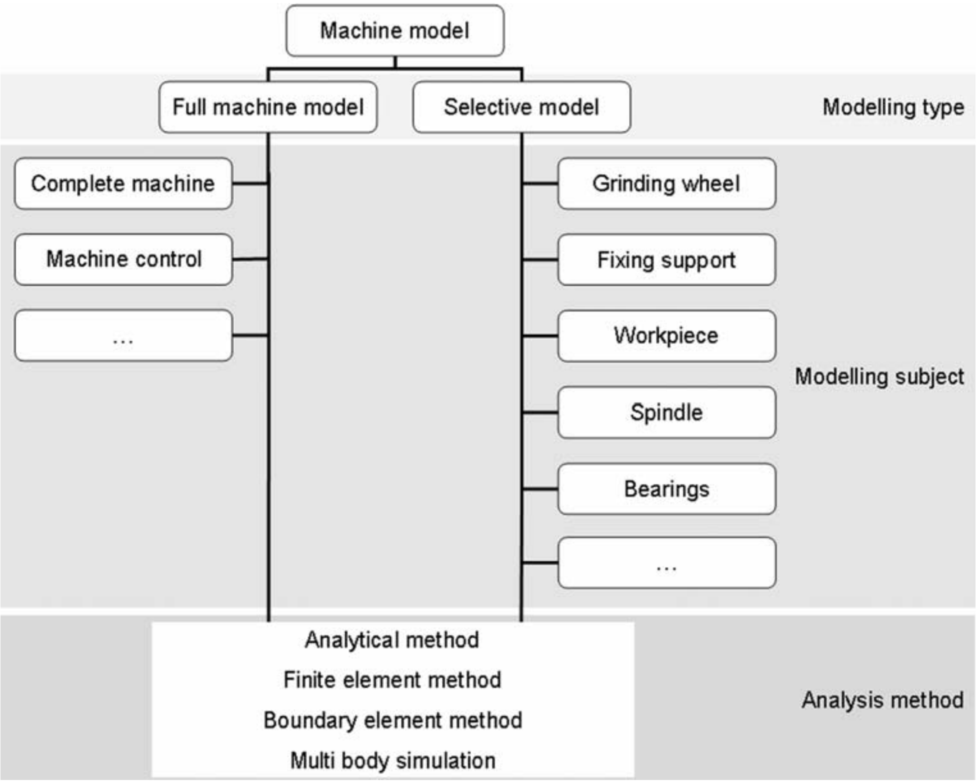


Fig. 6 Approaches for machine models

are considered in detail in a selective model. In this case parts with the highest effect on the process characteristics are modelled in detail whereas the remaining parts are included in the selective model only coarsely. The models can be based on analytical, finite element or boundary element methods, or on multi body simulations, depending on the process and grinding effects. A schematic overview of the modelling approaches is given in Fig. 6.

3.1 Full machine model

In a full machine model, the machine structure is described completely. Furthermore, the modelling of the machine control can be included in the machine model as well, especially for linear direct drives or five axes applications [16, 17]. During direction shifts in pendulum and speed stroke grinding processes forces and accelerations occur, which causing vibrations of the machine structure. These vibrations can only be considered by including the behaviour of the whole machine in the model. Another advantage of full machine models is the possibility of developing new machine tools with virtual prototypes [14]. Because of limited computing performance, compromises regarding the level of detail of a full machine model are necessary [18].

A current approach to build up a full machine model for an existing grinding machine is given by multi body simulations. Thereby the model parameters, like stiffness and damping properties, have to be identified. As a machine is very complex, abstractions are necessary to ensure computability. In a first step, the CAD model is used to create a FEM model of the machine. The behaviour of couplings, like the linear bearings e.g., are represented by spring damper elements to simplify the model without reducing the accuracy. In a second step, the stiffness properties of the elements are identified by matching the results of simulated or experimental modal analysis. With frequency response functions of the system the damping properties can be determined. The resulting multi body simulation computes the displacement of the machine structure due to given process forces [16, 19].

When high feed rates and impulses occur as in pendulum and speed stroke grinding, it is important to consider the motion of the workpiece table in relation to the grinding wheel. Therefore, a movable flexible multi body simulation that can take into account the path motion of the machine axes with specialized force subroutines is favoured [17, 20]. For representing the moving contact forces between workpiece table and machine the connection is realized by spring–damper elements with movable knots. Such a flexible multi body system for a linear

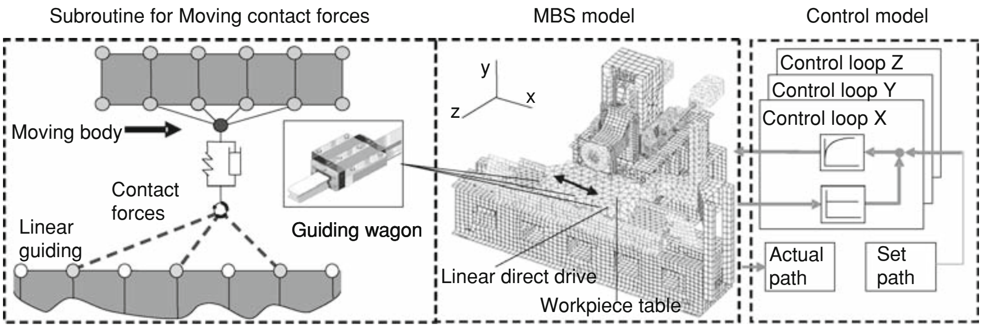


Fig. 7 Multi body system of a pendulum grinding machine [21]

bearing of a pendulum grinding machine is pictured in Fig. 7.

3.2 Selective model

If only some of the machine components react to an excitation by the grinding process, the machine model can be focused on these elements by describing them in detail. The remaining parts are included in the model only coarsely and with strong simplifications. Comparing the selective model with the full machine model, in the selective model the machine structure is represented with a higher level of abstraction and only some parts are modelled with more details. Modelling approaches are FEM, boundary element method, multi body simulations or analytical models [1, 2]. For parameterising a selective model, measurements of the real machine are necessary. In this section, two examples of selective models are presented, as shown in Figs. 8 and 9.

3.2.1 Spindle and grinding wheel

If the distribution of the process forces depends strongly on time and space, a detailed representation of the contact area between grinding wheel and workpiece is needed. This is the case in high-performance face grinding and, especially, in NC-shape grinding. One possible approach is to discretise the grinding wheel with finite elements, which leads to a well resolved contact surface. This method is able to include additional effects, like the expansion of the grinding wheel due to centrifugal forces at high rotational speed or thermal influences [4].

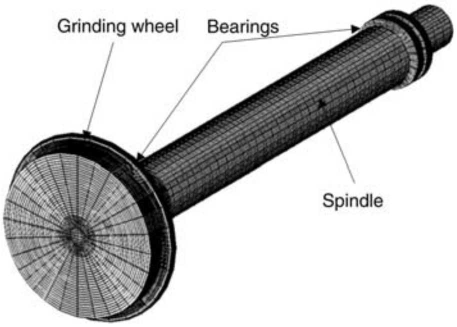


Fig. 8 Selective model of spindle and grinding wheel based on [11, 23]

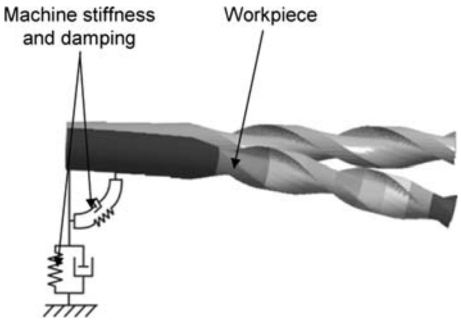


Fig. 9 Selective workpiece model based on [25]

The behaviour of the whole machine is reduced to selected parts or assemblies, which decreases the total modelling effort. One possible representation is to model an elastic grinding wheel support which includes the stiffness properties of the grinding machine [22]. Another possibility is to discretise the spindle with finite elements, and to concentrate the stiffness of the grinding machine in elastic bearings [11, 23]. This approach is shown in Fig. 8. Since the parameters of the bearings cannot be measured directly, numerical parameter identification techniques are used to determine them. In this approach, the results of measurements are compared to corresponding simulation results. Using optimization algorithms, the optimal parameters are computed by minimizing the distance between the measurement and the simulation results.

3.2.2 Workpiece

Grinding processes of very elastic workpieces require a precise simulation of the process, which can be approximated by analytical descriptions, FEM, or boundary element method [1, 2].

For grinding processes of long cantilevering workpieces, as drills and end mills in the manufacturing state, a beam model can be used for instance, which is illustrated in Fig. 9. The machine structure is reduced to the boundary conditions of the beam model [24]. Parameters for the elastic and damping properties of the clamping support have to be identified by measurements of the machine behaviour, e. g. using modal analysis or structural investigations [25]. With the parameterized analytical model, static and dynamic effects of the workpiece are predictable [5, 25, 26].

4 Coupling of process and machine model

The process and machine models described in the previous sections need to be coupled in order to simulate the interaction between grinding process and grinding machine. Although coupling problems are also encountered in other disciplines, such as in fluid-structure interactions or shape optimisation analyses, this section concentrates only on some aspects concerning grinding processes. These aspects, judged to be important for grinding simulations, have been extracted during studying different works done in the last years and will be discussed in the following in detail. Many coupling approaches are based on the exchange of the grinding forces, as predicted by the process model, and displacements, as computed by the machine model, Fig. 10 [5, 26]. Furthermore, heat, temperature and the shape of the contact area between grinding wheel and workpiece can be exchanged [27].

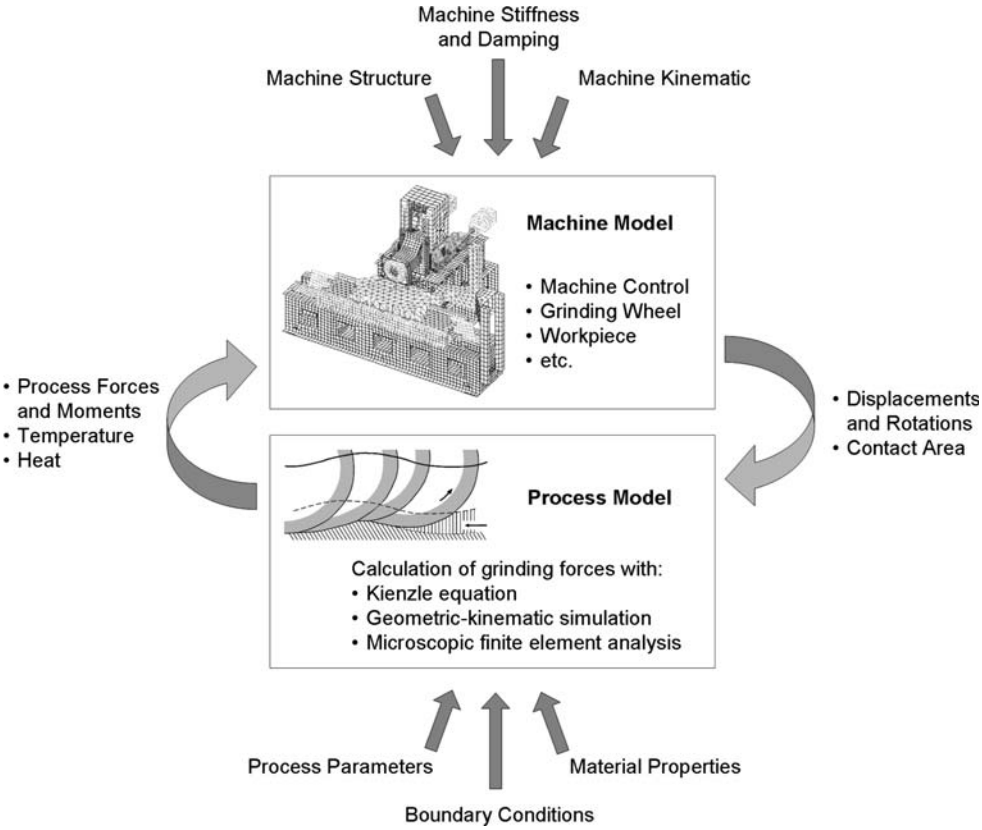
The complexity of a process–machine interaction is determined by the rules according to which the interaction takes place and the frequency of data exchange between the process and machine model [28].

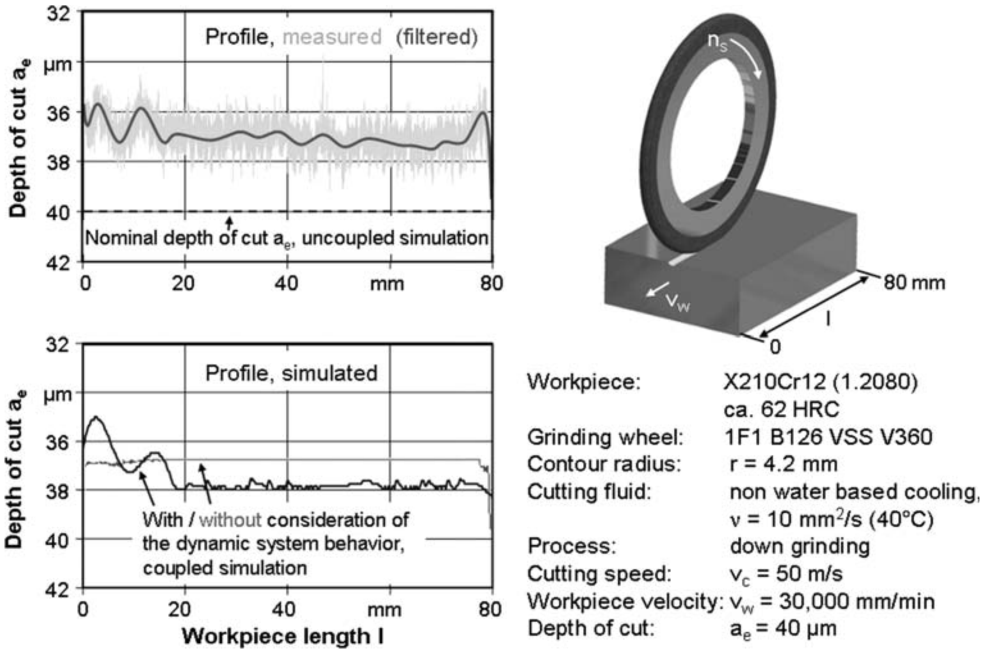
Since the process and machine state, in general, vary in time and additionally involve nonlinearities, the coupling problem has to be solved iteratively. So, for a certain time span, during which the process and the machine are considered, it may be necessary to perform several simulation iterations. Every time the process and the machine are in an equilibrium state, the problem is said to be converged for that iteration and the simulation can proceed to the next iteration, until the end of the considered time span is reached. An iterative solution for nonlinear process–structure coupling problems is presented in [23].

In order to evaluate the process and machine state after one iteration step, convergence criteria have to be defined. For a structural analysis, for example, forces or displacements are used as convergence criteria. An overview about coupling strategies and related convergence problems is for example given in [11].

In order to obtain accurate simulation results, sufficiently refined time increments and signals are needed. The

Fig. 10 Interaction between process and machine model





Workpiece: X210Cr12 (1.2080)
ca. 62 HRC
Grinding wheel: 1F1 B126 VSS V360
Contour radius: r = 4.2 mm
Cutting fluid: non water based cooling,
$\nu = 10\ \mathrm{mm^2/s}$ (40°C)
Process: down grinding
Cutting speed: $v_c = 50$ m/s
Workpiece velocity: $v_w = 30{,}000$ mm/min
Depth of cut: $a_e = 40$ µm

Fig. 11 Simulated and measured depth of cut of includes coupled and non-coupled simulation of process and machine models [23]

requirement of high accuracy may lead to a large number of iterations. Thus, the resulting computing time is long.

With some assumptions regarding the process, the machine, and the interaction, the simulation can sometimes be simplified. This simplification may lead to a significant reduction of the computing time, while the simulation results are still representative for the real process.

The mutual acquisition and transfer of simulation results between the process and machine model throughout coupling require adequate interfaces. Some interfaces are offered by commercial software. In other cases, it can be necessary to implement a self-developed software interface, which is fitted to the process and machine considered. In [29] interfaces between different grinding simulations are described.

Through coupling, the accuracy of the simulation results provided by a non-coupled process and machine model can be improved. In [23] it is shown how the simulation results for predicted workpiece topographies can be improved by taking the interaction between the process and the machine into account. As shown in Fig. 11, the simulation results based on coupled process and machine models consider the influence of the dynamic machine behaviour and, therefore, match the measured workpiece surface profile more precisely than the non-coupled solution.

5 Conclusions

Simulation of grinding is still an academic-driven field of research accounting for many different simulation approaches which today mainly focus on grinding wheel–workpiece interaction inside the contact zone. Those simulations primarily help to increase the understanding of a grinding process with its millions of single grain engagements resulting in a macroscopic material removal.

This article presents further developments in the field of modelling and simulation of grinding with the focus on process–machine interaction. Models describing the grinding process and models describing the machine structure are coupled in order to simulate process–machine interactions. The modelling and simulation is partly done using commercial software packages. However, in most cases no appropriate commercial software packages are available and therefore special software solutions are programmed. The presented simulation approaches are based on four different grinding processes, namely face grinding, speed stroke grinding, tool grinding, and NC-shape grinding. Concerning the process models, macroscopic as well as microscopic approaches describing the grinding wheel–workpiece contact are used. Grinding forces are calculated as input parameters for the machine model. The force models are mostly based on an adapted Kienzle equation. For modelling the structure of the grinding machine, those machine components which cause the main deformations and displacements between grinding wheel and workpiece are identified and modelled. Furthermore, the modelling of the grinding machine strongly depends on the current process setup, e.g., the grinding kinematics, the material and shape of workpiece, and the properties of the grinding wheel.

Within this article different modelling approaches describing the different components of the grinding machine are presented. As mentioned, a coupling of machine and process models is necessary to simulate process–machine interactions. Thereby, different coupling strategies to connect process and machine model have been discussed. Furthermore, the frequency and amount of data for the coupling procedures could be varied which influences the overall simulation result and quality.

The main improvements of coupled simulations are the more precise prediction of grinding forces and workpiece topographies, as well as the behaviour of the machine structure, e.g., deformations and vibrations during the grinding process. On the one hand, process parameters optimized for the respective grinding machine can be identified. On the other hand, tool path optimization and the identification and improvement of weak points of the machine structure are possible.

Future research field is the exchange of temperature or thermal parameters between the process and the machine model, additionally to the exchange of grinding forces and deformations within the coupling procedures. Moreover, CFD simulations for detailed description of the effects caused by the cooling lubricant can be coupled into the simulations.

Concerning the software architecture of the coupled simulations, mostly accounting for several independent software tools covering the machine and the process, integral software tools covering both the process and the machine will be focused in the future.

Acknowledgments This research work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) within the Priority Program 1180 “Prediction and Manipulation of Interaction between Structure and Process”. The authors wish to express their sincere thanks to further co-workers for their effort in helping to write this paper, namely A. Bouabid, M. Deichmüller, M. Duscha, P. Herzenstiel, F. Hoffmann, K. M. Popp, A. Rademacher, A. V. Scheidler, M. Weiss, and S. Wiedemann.

References

1. Brinksmeier E, Aurich JC, Govekar E, Heinzel C, Hoffmeister HW, Peters J, Rentsch R, Stephenson DJ, Uhlmann E, Weinert K, Wittmann M (2006) Advances in modeling and simulation of grinding processes. Ann CIRP 55(2):667–696
2. Tönshoff HK, Peters J, Inasaki T, Paul T (1992) Modelling and simulation of grinding processes. Ann CIRP 41(2):677–688
3. Hou ZB, Komanduri R (2003) On the mechanics of the grinding process—Part 1. Stochastic nature of the grinding process. Int J Mach Tools Manuf 43:1579–1593. doi:10.1016/S0890-6955(03)00186-X
4. Mackerle J (2003) Finite element analysis and simulation of machining: an addendum. A Bibliography (1996–2002). Int J Mach Tools Manuf 43:103–114. doi:10.1016/S0890-6955(02)00162-1
5. Denkena B, Tracht K, Deichmüller M (2006) Wechselwirkungen zwischen Struktur und Prozess beim Werkzeugschleifen. wt Werkstattstechnik online, Jahrgang 96, H. 11/12
6. Zitt U-R (1999) Modellierung und Simulation von Hochleistungsschleifprozessen. Dissertation, University of Kaiserslautern
7. Kienzle O (1954) Einfluss der Wärmebehandlung von Stählen auf die Hauptschnittkraft beim Drehen. Stahl Eisen 74:530–551
8. Braun O (2008) Konzept zur Gestaltung und Anwendung definiert gesetzter CBN Schleifscheiben. Dissertation, Universität Kaiserslautern
9. Klocke F, Duscha M, Hoffmann F, Wegner H (2008) Prozess-Maschine-Wechselwirkung beim Pendel- und Schnellhubschleifen mit hochharten Schleifscheiben. Diamond Buisness 3(2008):52–60
10. Weinert K, Blum H, Jansen T, Mohn T, Rademacher A (2006) Angepasste Simulationstechnik zur Analyse NC-gesteuerter Formschleifprozesse. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb 101(7–8):422–425
11. Weinert K, Blum H, Jansen T, Rademacher A (2007) Simulation based optimization of the NC-shape grinding process with toroid grinding wheels. Production engineering—research and development. Springer, Berlin, 1/3:245–252
12. Biermann D, Mohn T (2008) A geometric-kinematical approach for the simulation of complex grinding processes, CIRP Intelligent Computation in Manufacturing Engineering, Innovation and Cognitive Production Technology and Systems, Naples, Italy
13. Neidhold T, Blochwitz T, Schreiber U (1999) Kooperation von Simulatoren durch Kopplung. 8. GMM-WS “Methoden und Werkzeuge zum Entwurf von Mikrosystemen”, 2.-3.12. 175–182, Berlin
14. Altintas Y, Brecher C, Weck M, Witt S (2005) Virtual machine tool. Ann CIRP. Keynote Pap STC-M 55(2)
15. Source: BLOHM Maschinenbau GmbH, Profimat MT 408 HTS
16. Weck M, Queins Q, Brecher C (2003) Coupled simulation of control loop and structural dynamics. Ann Ger Acad Soc Prod Eng X(2):105–110
17. Brecher C, Queins M, Witt S (2004) Coupled simulation of structural dynamics and control loops for the development of high-dynamic machine tools. In: Proceedings of NAFEMS seminar “Mechatronics in Structural Analysis”, Wiesbaden
18. Werner K, Klocke F, Brinksmeier E (2003) Modelling and simulation of grinding processes. In: 1st European conference on grinding. Aachen, S. 8–1–8–27
19. Queins M (2005), Simulation des dynamischen Verhaltens von Werkzeugmaschinen mit Hilfe flexibler Mehrkörpermodelle. Dissertation, RWTH Aachen
20. Hoffmann F, Brecher C (2006) Simulation dynamischer Bahnabweichungen von Werkzeugmaschinen. In: Proceedings of VDI conference “Elektrisch-mechanische Antriebssysteme”, Düsseldorf, VDI
21. Klocke F, Duscha M, Hoffmann F, Wegner H, Zeppenfeld C (2008) Machine–grinding wheel–workpiece interaction in speed stroke grinding. In: Proceedings of the 1st international conference on process machine interaction, pp 259–266
22. Herzenstiel P, Ching CY, Ricker S, Menzel A, Steinmann P, Aurich JC (2007) Interaction of process and machine during high-performance grinding—towards a comprehensive simulation concept. Int J Manuf Technol Manage 12(1/2/3):155–170
23. Jansen T (2007) Entwicklung einer Simulation für den NC-Formschleifprozess mit Torusschleifscheiben. Dissertation, Technische Universität Dortmund, Essen, Band 43
24. Denkena B, Deichmueller M, Kroeger M, Panning L, Carstensen C, Kilian S (2007) Modeling and simulation of the process machine interaction during tool grinding processes. In: Proceedings of the 10th CIRP international workshop on modelling of machining operations, 27–28.8.2007, Reggio Calabria, Italy
25. Popp KM, Kröger M, Deichmueller M, Denkena B (2008) Analysis of the machine structure and dynamic response of a tool

grinding machine. In: Proceedings of the 1st international conference on process machine interaction, pp 299–307

26. Denkena B, Deichmueller M, Kröger M, Popp KM, Carstensen C, Schroeder A, Wiedemann S (2008) Geometrical analysis of the complex contact area for modeling the local distribution of process forces in tool grinding. In: Proceedings of the 1st international conference on process machine interaction, pp 289–298
27. Malkin S, Guo C (2007) Thermal analysis of grinding. CIRP Ann Manuf Technol 56(2):760–782
28. Herzenstiel P, Bouabid A, Steinmann P, Aurich JC (2008) Experimental investigation and computational simulation of process–machine interactions during high-performance surface grinding. In: Proceedings of the 1st international conference on process machine interaction, pp 267–278
29. Weinert K, Blum H, Jansen T, Mohn T, Noyen M, Rademacher A (2007) Verfahrensspezifische Modellbildung für die Belastung beim Schleifen. In: Hoffmeister H-W, Denkena B: Jahrbuch Schleifen, Honen, Läppen und Polieren, Vulkan-Verlag, Essen, 63:24–38