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ORIGINAL ARTICLE

Simulation-based thermal investigation of the cutting tool in the environment of single-phase fluxes

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Abstract The thermo-energetic evaluation of machine tools, primarily focusing on the tool and its chuck, is very important for manufacturing accuracy. The temperature fields in the cutting tool and the clamping system can be intentionally influenced by air cooling. The cooling influence cannot be readily evaluated in practice. However, making use of simulation models, it is possible to identify the most essential parameters and to propose process-related optimal input variables. In these models, the relevant air fluxes around the tool have to be considered. The challenge is to define all of the boundary and transfer conditions. The simulation model can be verified by experiments, which, in turn, make it possible to substantiate the outcomes at relevant positions.

Keywords Machine tools · Thermo-energetic investigation · Heat transfer · Flux simulation · Tool

1 Introduction and objective

In dry machining processes, the lack of cutting fluids lends itself to significant advantages. Energy consumption and/ or costs are diminished, hazards to human health are diminished, and the parts remain uncontaminated and free of residues, on the one hand. On the other hand, however, the requirements of the process must fulfil increase.

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Cutting materials that can withstand high thermal loads have to meet the demands of the tool. Air cooling can be effective for chip removal and the reduction of thermo-elastic deformations [1]. If one succeeds in directing the air fluxes specifically on the tool so that heat is sufficiently dissipated, then thermal dislocations are reduced, which, in turn, results in an increase in the manufacturing accuracy. An overview of the coolant concepts offers [2]. The perspectives of the dry machining are described in [3]. Motivated by the advantages of the dry machining, a simulation model is now focused which allows an assessment of the influence of the ambient air flows.

To be able to evaluate the efficiency of air cooling, it is necessary to operate with a suitable model of the real process. For this purpose, mathematical models are used [4]. Modelling makes use of the heat transfer laws, which can be represented by the three heat transfer mechanisms of thermal conduction, radiation and convection; they can also be universally formulated as the relationship between effect and cause, whereby the effect refers to the flux of the transfer variable, whereas the cause is represented by the gradient [5]. In some cases, fluid fluxes were considered.

A numerical simulation model approximates the heat fluxes and makes it possible to calculate the relevant parameters. Experimental studies take a great deal of time and are expensive in their setup; in principle, they do not allow any evaluation of the corresponding thermal transfer mechanisms. Thanks to the outcomes, which are close to practice, experiments can be employed to verify the simulation model. So far, simulation-based investigations were carried out on the drill and rotary tool [6–9]. Based on existing knowledge, externally fluxes are being investigated now, which can be considerably turbulent particularly when it hits the tool.

This publication describes an approach for step-by-step modelling of air cooling for selected metal removal supported by simulation. The experimental explorations verify the simulation model at a very important point and, afterwards, expand the model by introducing other issues, such as the complex cutting tool edge, as well as separately excited air flows (see Fig. 1). The input variables are varied and their effects are calculated, so that it becomes possible to evaluate the cooling effect for cooling scenarios.

2 Influencing parameters and subject of investigation

The temperature field ϑ inside the tool, which is directly proportional to thermal elongation and thus immediately affects manufacturing accuracy, is a function of time t and position $\overline{x}$. It is significantly influenced by numerous technical parameters:

$$\vartheta = f\left(\overline{x}, t, Q_P, \alpha_{C,WS}, \alpha_{WU}, \alpha_{C,SM}, \alpha_{SU}, n, d_D, \vartheta_D, v_D\right)$$

The values of the influencing parameters can be set in the simulation model. For this publication, investigations are limited to the influence of air flow and its tempering when passing the nozzle (see Fig. 2). To do this, a cutting process with end mill was chosen, and air flow temperature and velocity were varied for a 4 mm nozzle diameter.

The corresponding parameters are depicted in Fig. 2, with

Q_P Process heat
$\alpha_{C,WS}$ Thermal contact resistance between tool and chuck
α_{WU} Heat transfer from tool to environment
$\alpha_{C,SM}$ Thermal contact resistance between chuck and motor spindle
α_{SU} Heat transfer from chuck to environment
n Speed
d_D Nozzle diameter
ϑ_D Air temperature at nozzle exit
v_D Air velocity at nozzle exit

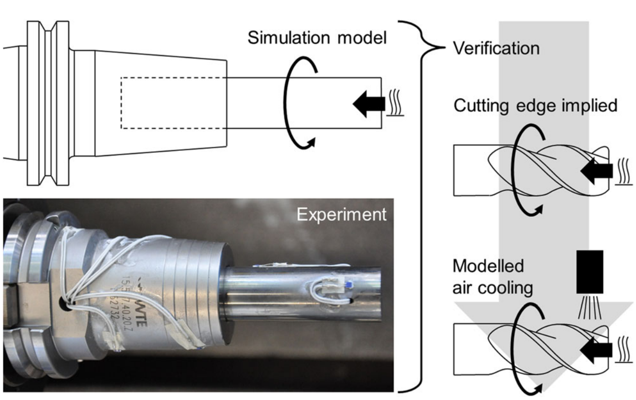

Fig. 1 Exploration approach

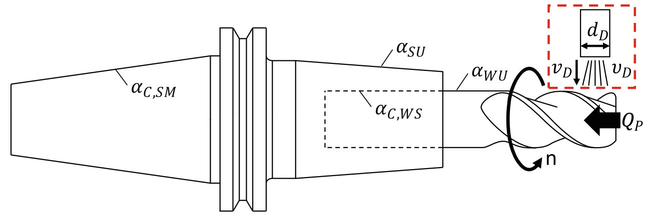

Fig. 2 Parameters influencing the temperature field in and around the tool and the chuck

3 The simulation model

At first, the simplified tool chuck and the tool, initially without cutting edge, are meshed (see Fig. 3). A virtual space, which is able to represent (map) the relevant air fluxes that immediately affect the tool's temperature field, is modelled around the tool and its chuck. Both the meshing and the calculation were carried out in Ansys 14.0 Workbench. In areas of high flux gradients and interfaces, an unstructured mesh of tetrahedral elements was chosen. Hexahedral elements were also used order firstly to realize a connection to the unstructured mesh and also to depict the wall contours better. Therefore, interfaces are included very well.

With a view towards the cutting tool and the process heat, the energy ratio introduced into the tool, depending on the corresponding cutting conditions, ranges from 10 to 20 % [10]. The process heat amount cannot be defined universally and depends on many process boundary conditions. The amount of the heat source affecting the TCP in experiments, which is also assumed in the model, corresponds to real cutting heat sources, as proven in [11], and results in a temperature level of 115.5 °C in the range of the cutting edges. The rotational speed is defined to be 1000 rpm. This parameter is commensurable with respect to real metal removal and can be implemented in experiments, thus enabling verification [12].

The simulation model consists of six domains and nine interfaces. A domain describes each physical domain (fluid, porous or solid) as tool chuck or the ambient area. Fluid domains are calculated with the turbulence model shear stress transport (SST), which delivers proven calculations in comparison with other wall models. They are established in the technical area [13]. Each interface defined the respective boundary region. Moreover, in the model, buoyancy forces are applied and continuous properties of the fluid are defined. The thermal properties of the model are shown in Table 1. The parameters were taken from the material database.

The contact condition between the tool and the chuck is defined by the general connection interface. It is a powerful way to connect regions in Ansys Workbench, by different grids or pitch changes.

The tool is clamped over the entire surface in the chuck. Depending on the surface properties, there is no established calculation approach [15]. In addition, past research shows in this area a very small temperature gradient [12]. Therefore, the contact resistance was neglected.

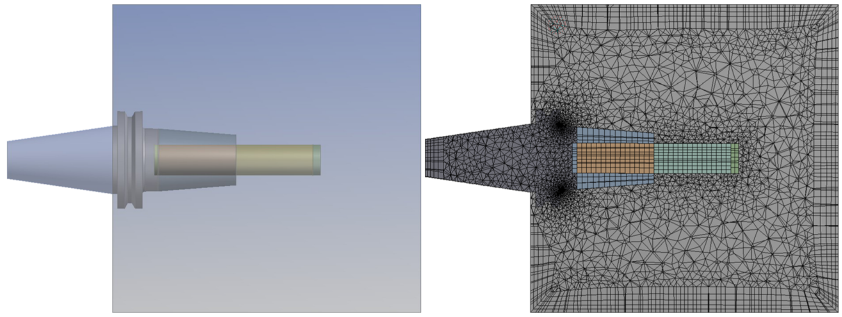

Fig. 3 Meshing of the simulation model

At the beginning, the temperature fields are calculated inside the tool and the clamping system, without the real cutting edge, as well as air cooling. The temperatures diminish homogeneously in the rotational axis direction; heat is emitted homogeneously into the environment. Additionally, the flow rates grow due to the mounting diameters along the rotational axis, which, in turn, cools down the temperature field more and more. Not only should the self-excited flows around the tool and the clamping system be taken into account but also the flows caused by natural convection, which were defined by gravity models in the boundary conditions of the simulation model. In Fig. 4, the associated temperature field of the tool and its clamping system, as well as of the air, are shown.

4 Experimental studies

For the experimental studies, a test bed with measuring instruments (see Fig. 5) enabling various measuring methods was put into operation. The tool and its clamping element were mounted in a motor spindle. This spindle is operated by a control and is fixed on a machine tool table with a supporting element. The measuring procedure is described in detail in [12]. Another publication includes the representation of simulated heat fluxes that were verified by means of values gained in experiments and can thus be transferred to other metal removal procedures via correction coefficients [14].

For this test series, process heat was introduced inductively. Thus, we succeeded in heating the tool both efficiently and in a contact-less manner. Temperature is measured on the tool and the clamping system at defined positions. Temperature can be measured at positions that are difficult to access by means of thin-film sensors (resistance thermometer Pt1000). The test bed also makes it possible to measure displacements with contactless eddy-current and laser sensors.

Table 1 Thermal properties of tool and clamping system

	Material	Thermal conductivity	Heat capacity
Tool	Carbide (WC=90 %, Co=10 %)	$25\,\frac{W}{m\cdot K}$	$460\,\frac{J}{kg\cdot K}$
Chuck	1.2343	$85\,\frac{W}{m\cdot K}$	$213.5\,\frac{J}{kg\cdot K}$

Figure 6 shows a schematic view of both the tool and the clamping system. The temperature curves were recorded for a speed of 1000 rpm at the measuring points 1 to 6. For this case, the stable state is established after about 3 h. In the cooling-down procedure, it can be seen that the temperatures plateau at 30 °C. This behaviour is due to the motor spindle's cooling cycle, which is adjusted to a constant temperature of 30 °C. There is a homogeneous drop in temperature along the rotational axis.

Before discussing the simulation results in detail, a special case of the simulation model is adjusted with the experiment. According to that case, the temperature fields are mapped with the corresponding input variable from process heat in the simulation model for a defined rotational speed. This can be taken as the basis to integrate the real cutting edge as well as externally induced fluxes.

The results from the simulation coincide with values from experiments (see Fig. 7). Greater deviations appear at the TCP and in the steep angle region. Deviation around the TCP is attributed to the difference in heating. Inductive heating was conducted at the test bed. Heat flux is introduced upon via tool face in the simulation model. Heat transfer is calculated based on models from [15] in the contact area of the steep angle. Both the roughness values required and the contact pressure required, as well as the models themselves, are characterised by

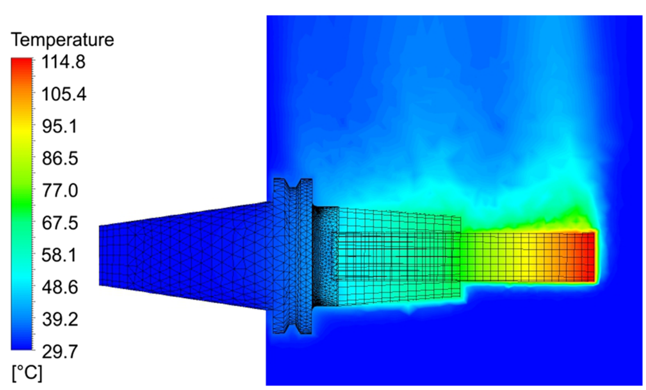

Fig. 4 Calculated temperature field on the tool (according to simulation model)

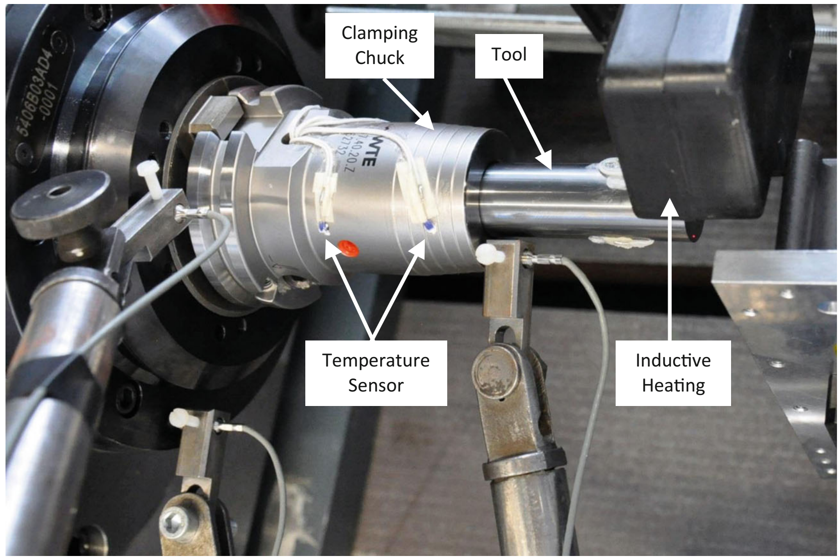

Fig. 5 Test bed equipped with measuring instruments

uncertainties. In principle, the results obtained from simulation and experiment correlate well.

5 Air cooling influence on the tool

The air exit velocity values of 5, 10 and 15 m/s were simulated. In addition, air fluxes whose temperature is by 5 or 10 K lower than the environmental air were simulated. The parameters were chosen so as to make it possible to estimate the cooling effect by employing the stationary compressed air supply.

As a result of the rotating speed, the air jet strikes a changing position on the tool. Process heat is defined continuously over the tool face. Consequently, the highest temperatures are determined around the TCP, and they drop in the tool chuck direction. Heat is removed by convection caused by the air fluxes. In Fig. 4, the temperature field is represented without air cooling. Figure 8 illustrates the temperature fields with air cooling.

The effects of the externally excited air fluxes are shown in Fig. 9. The temperatures at point 1 are diminished by at least 25 K, and drop much more along the clamping system, if air cooling is used (see Figs. 7 and 9). Even if the air flux of 5 m/s velocity is not tempered, the temperatures drop down below 80 °C. If the air is additionally cooled down by 5 or 10 K, the cooling effect increases slightly. For this test series and the selected parameters, it could be seen that externally excited air fluxes significantly affect both temperature field and tool.

To demonstrate the cooling effect by the externally excited air flux for the process parameters defined, measuring point 1

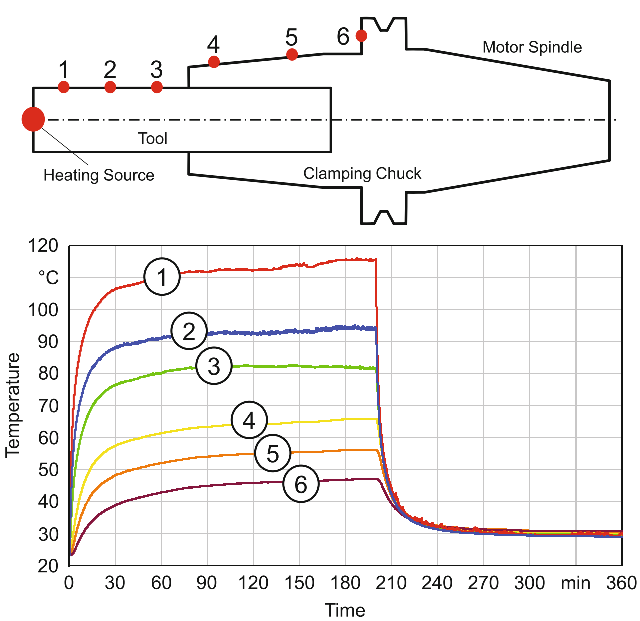

Fig. 6 Temperature field on tool and clamping system obtained during the experiments

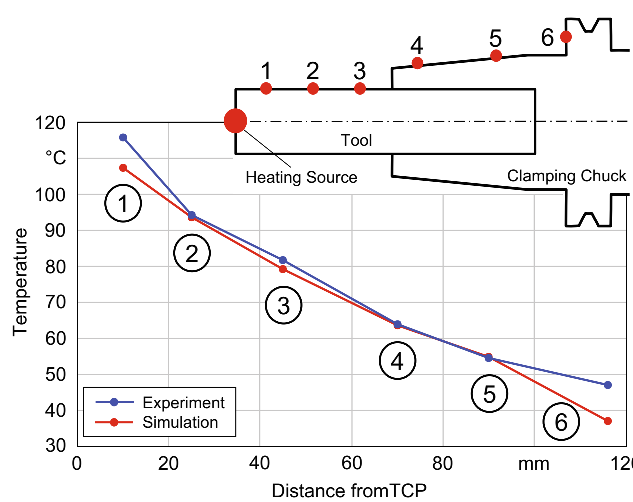

Fig. 7 Temperature fields from experiment and simulation at 1000 1/min—in comparison

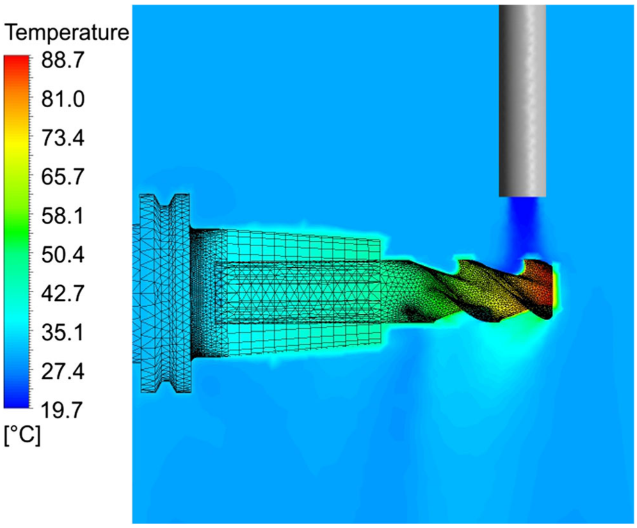

Fig. 8 Air cooling on the tool at a flow rate of 5 m/s and air cooled down by 10 K

is considered as an example. Figure 10 illustrates the temperature curve as a function of the flux rate for various air fluxes. Simulations were conducted without cooling and with three different flux rates. Interpolation of the positions between the measuring points did not make sense. Therefore, initially, a linear relationship was established. This makes it clear that the cooling effect strongly increases even at low flux rates. At 5 m/s, and afterwards, the cooling effect is less pronounced. Allowing for an absolute temperature in the workspace of around 30 °C, then the relative heating in the region of the cutting edge of almost 80 K can be reduced by externally induced air fluxes by around 50 % (40 K).

Consequently, air cooling influenced considerably the temperature field of the tool and the chuck. Tempering of the supplied air has small influence. According to the results, the flow velocity should be 5 m/s. However, the course should be confirmed and expanded by further studies. In addition,

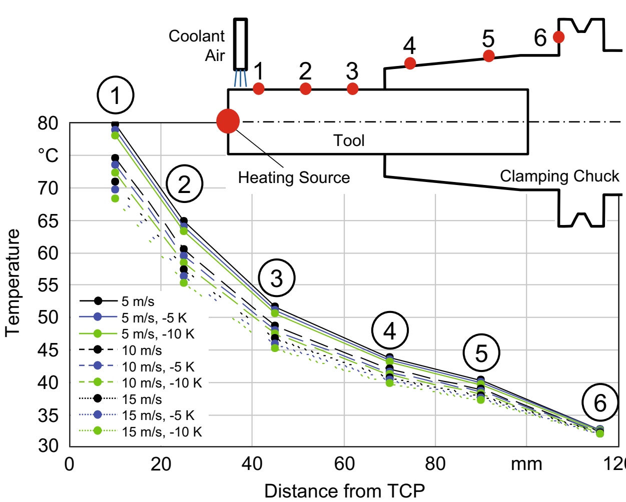

Fig. 9 Calculated temperatures at various cooling strategies

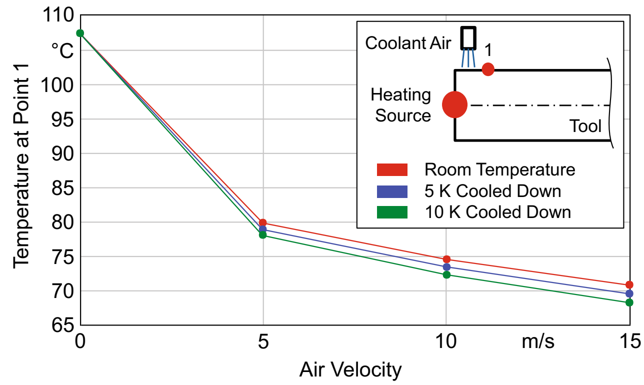

Fig. 10 Temperatures at measuring point 1 at tempered air cooling

experimental investigations with air currents are essential. For this, the test stand needs to be extended systematically. This is time consuming and demanding but very important for the verification of the results.

It is also conceivable that the turbulence at the cutting edge by the externally excited air fluxes are larger than those calculated with the simulation model. For this, basic research can be done and turbulence models of fluid mechanics are applied. Perhaps, as a consequence, the heat flux will be less well dissipated.

6 Summary and outlook

A simulation model for chip removal processes was generated against the background of air fluxes. The boundary conditions were selected in a way that both real process variables could be mapped and experimental investigations could be performed. The simulation model was verified by means of the experiments. The temperature fields were explored for selected process parameters and evaluated. It was possible to show that separately excited air fluxes, whose original function is chip removal, offer an efficient and targeted cooling of the tool as a function of the process parameters.

For the explorations based on simulations, further flow rates and higher heat fluxes will be introduced in the future in order to validate the estimation from Fig. 10. Moreover, it makes sense to carry out a structural analysis afterwards in order to calculate the thermo-elastic dislocations.

The cooling effect of the tool at higher process-realistic speed values has to be investigated in experiment in almost real time; consequently, the test bed has to be redesigned. Furthermore, explorations aimed at energy consumption for air tempering, and its influence of tool cooling, are needed.

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References

1. Wieland P (2005) Ein Beitrag zur Gestaltung der Spanentsorgung bei der Trockenbearbeitung. Dissertation, Verlag Wissenschaftliche Scripten, Auerbach
2. Weinert K (1999) Trockenbearbeitung und Minimalmengenschmierung, Einsatz in der spanenden Fertigungstechnik. Springer Verlag, Berlin
3. Steibl J, Schillo E, Lanegger J (2001) Chancen und Grenzen der Trockenbearbeitung - Anforderungen, Einsatzmöglichkeiten, Erfahrungen, Grenzen und Perspektiven. VDI-Berichte 1635: Trocken oder nass - wohin geht die Metallbearbeitung Tendenzen in der Kühlschmierstoffanwendung, VDI-Gesellschaft, pp. 19–32
4. Pabst R (2008) Mathematische Modellierung der Wärmestromdichte zur Simulation des thermischen Bauteilverhaltens bei der Trockenbearbeitung. Forschungsberichte aus dem wbk Institut für Produktionstechnik, Dissertation, Shaker Verlag
5. Marek R, Nitsche K (2012) Praxis der Wärmeübertragung. Carl Hanser Verlag, Munich
6. Fallenstein F, Aurich JC (2014) CFD based investigation on internal cooling of twist Drills. 6th CIRP International Conference on High Performance Cutting, Volume 14:293-298. doi:10.1016/j.procir.2014.03.112
7. Schindler S, Zimmermann M, Aurich JC, Steinmann P (2014) Finite element model to calculate the thermal expansions of the tool and the workpiece in dry turning. 6th CIRP International Conference on High Performance Cutting, Volume 14:535-540. doi:10.1016/j.procir.2014.03.087
8. Liang L, Quan Y (2013) Investigation of heat partition in dry turning assisted by heat pipe cooling. Int J Adv Manuf Technol 66(9–12):1931–1941. doi:10.1007/s00170-012-4471-y
9. Liang L, Quan Y, Ke Z (2011) Investigation of tool-chip interface temperature in dry turning assisted by heat pipe cooling. Int J Adv Manuf Technol 54(1–4):35–43. doi:10.1007/s00170-010-2926-6
10. Großmann K, Jungnickel G (2008) Thermische Modellierung von Prozesseinflüssen an spanenden Werkzeugmaschinen. Institute of Machine Tools and Control Engineering, Technische Universität Dresden. ISBN: 978-3-86780-089-1
11. Komanduri R, Hou ZB (2001) Thermal modeling of the metal cutting process. Part III: temperature rise distribution due to the combined effects of shear plane heat source and the tool–chip interface. Int J Mech Sci 43:89–107. doi:10.1016/S0020-7403(99)00070-3
12. Drossel W-G, Wittstock V, Bräunig M, et al (2013) Untersuchung der thermischen Werkzeugverformung. wt Werkstattstechnik online 103(11/12):543–550. ISSN:1436–4980
13. Menter FR, Kuntz M, Langtry R (2003) Ten years of industrial experience with the SST turbulence model. In: Hanjalic K, Nagano Y, Trummers M (eds) Turbulence, heat and mass transfer 4, Begell House Inc.
14. Drossel W-G, Wittstock V, Schmidt G et al (2014) Thermal deformations of cutting tools: measurement and numerical simulation. Prod Eng 8(4):543–550. doi:10.1007/s11740-014-0538-y
15. Kneer R, Vieler S, Großmann K, et al. (2013) Messungen des Wärmeübergangs an Fugenkontakten von Werkzeugmaschinen. 16. Werkzeugmaschinen-Fachseminar, TU Dresden. http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-118570