Thermo-elastic deformation of rotary axes

Brecher, C.; Spierling, R.; du Bois-Reymond, F.; Fey, M.
Werkzeugmaschinenlabor WZL der RWTH Aachen

Abstract

Additive manufacturing has emerged as a fast growing field within the manufacturing technologies. Established machine tool manufacturers recently presented machine tools combining milling and laser welding. With these, machine tools can realize a higher degree of flexibility and a shorter production time resulting in a higher productivity. However there are challenges that have to be maintained to achieve the necessary machining accuracy, especially due to thermal effects arising through the use of high power laser processing units. Causes of dimensional and geometric errors in products manufactured on machine tools are insufficient geometrical and kinematic behaviour from the production and assembly of the machine, insufficient static stiffness, poor dynamic behavior of structure and/or feed drives and thermal deformation.

To study the thermal behavior of laser-integrated machine tools, it is essential to analyze and simulate the thermal behavior of machine components, both, individually and assembled. Thermal errors can have a big influence on machining precision of machine tools depending on the material of the structure, the elongated lengths and the temperature field. Considering these effects will help design a geometrically stable machine tool under the influence of high power laser processes.

This paper presents a method to determine the loss of machining precision due to thermal impacts. Real effects of laser machining processes are considered and thus enable an optimized design of the machine tool, in the early design phase with respect to its components. Core element of this approach is a updated FE-Model considering all relevant variables arising, e.g. laser power, angle of laser beam, reflective coefficients and heat transfer coefficient. Hence a systematic approach to obtain this updated FE-Model is essential. Indicating the thermal behavior of structural components as well as predicting the laser beam path, to determine the relevant beam intensity on the structural components, are the two constituent aspects of the method. To verify the model both aspects of the method have to be combined and verified empirically. To be able to measure the actual errors of the rotary axis, a measurement setup and analysis is

presented. Thereby all boundary conditions for an indirect compensation are fulfilled. The knowledge from the model and control-internal data can then be used to build up an indirect volumetric compensation of the machine errors.

In this context, simulation models have been built up and experimental investigations have been performed to predict the distribution of the laser beam intensity as well as the resulting temperature field. Furthermore, an experimental setup to measure the geometric deviations directly on the machine tool was developed to be able to verify simulations with empirically gained results. A machine table with a rotary axis as a central machine component was chosen to serve as a demonstrator because of its importance for maintaining machining precision.

Finally, it is shown that the method and a good understanding of the two core aspects, the thermal machine behavior and the laser beam path, as well as their combination help designers to minimize the loss of precision in the early stages of the design phase. In addition, the knowledge helps to built up an indirect compensation in the use phase. So the method contributes to the optimization of machining precision due to thermal impacts in the design as well as in the use phase.

1 Introduction

The constant demand for high precision parts with complex geometries and machining tasks is a driver for the need to increase the machining precision of five-axis machine tools [1].

The accuracy of machine tools is influenced by their static, dynamic (structure and drives), kinematic and thermal behavior, the geometry, the capability of the control system and the assembly, Figure 1.

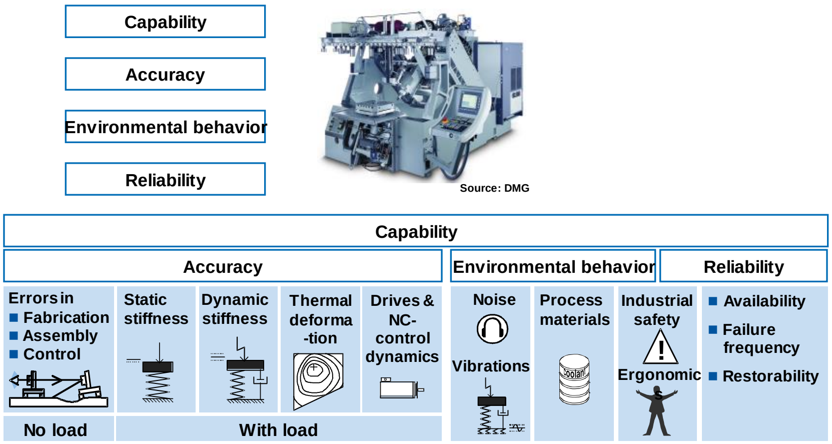


Figure 1: Capability of machine tools [2]

The thermal errors of machine tools can be up to 75% of the machine tool’s total error. [3] They are induced by power losses of the drives (resistance losses) and the kinematic system (e.g. friction in bearings and guidance systems), thermal influences of the machining process (e.g. heat from the chip forming process) and environmental thermal flows (e.g. workshop climate). These influences cause an instationary temperature field and an accordingly instationary deviation field of the machine structure [4]. Finally the relative deviation of the TCP to the workpiece leads to errors in the machining result, Figure 2 [5].

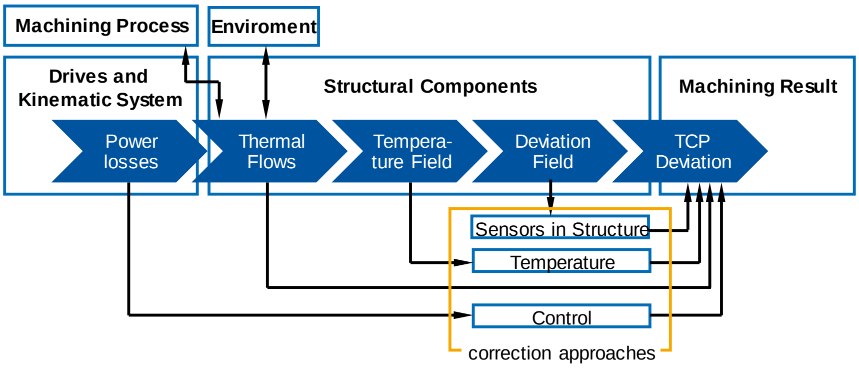


Figure 2: Thermo-energetic functional chain and compensation approaches [5]

There are different approaches to correct these TCP deviations. They can all be sorted into two categories, direct and indirect compensation. While the direct compensation measures the deviation of the TCP, the indirect compensation is characterized by mathematical models, that try to correlate the TCP deviation with measurands that originate from earlier chain links of the thermo-energetic functional chain. Afterwards both methods compensate the TCP deviation in the volume [6].

This paper focuses on the indirect compensation methods of which four approaches are presented here. One approach is to measure the local structural deviations with sensors integrated into the machine assembly and calculate the TCP displacement [7]. Another approach is to measure temperatures at a small number of points to determine the error at the TCP [8]. Both approaches have the advantage of measuring effects that are close to the final chain link of the functional chain. This reduces the errors due to simplifications and assumptions, as there are less of them and they pass less stages of the system.

A third concept is to use control internal data such as feed power and revolutions per minute (rpm) to determine the displacement [6]. In this case the environmental influence can not be predicted, what leads to a worse prediction compared to the two concepts mentioned before.

In addition, there is a mixed approach that combines several of the data acquisition points. This approach tries to combine the advantages of all strategies without their disadvantages [6].

2 Heat Transmission in Machine Tools

During the last years there has been a lot of research in the field of thermo-elastic behavior of machine tools [6;7;8;9]. Many of these research efforts aim at predict the time variant behavior of the structure to be able to correct it. If the TCP deviation in the volume is known, a compensation on the control can be performed. As the deviation is the result of the functional chain, from Figure 2, the causes at the beginning of the chain need to be considered in the first place to calculate the TCP deviation, Figure 3. The focused research programs cover a lot of research concerning the single influences and its prediction. The influences are cooling systems, if existent, friction contacts in the elements of the kinematic system, the machining process, the power losses of the drives and the environment. Cooling systems are not necessarily part of a machine tool, but as every motor spindle has a one, they are a common influence. The cooling effect can be simulated with the method shown in [10]. The elements of the kinematic system, such as bearings and guidance, induce heat flows to the structure due to friction. The prediction of the resulting temperature field is a matter of research. [11]. There are various processes in machine tools with very diverse thermal influences. The prediction of the influences is a recent scientific topic, e.g. milling [12], grinding [13] or laser based machining [14]. The losses in actual drives and their prediction are also a topic of interest in research. The influence of the environment can be taken into concern. [6]

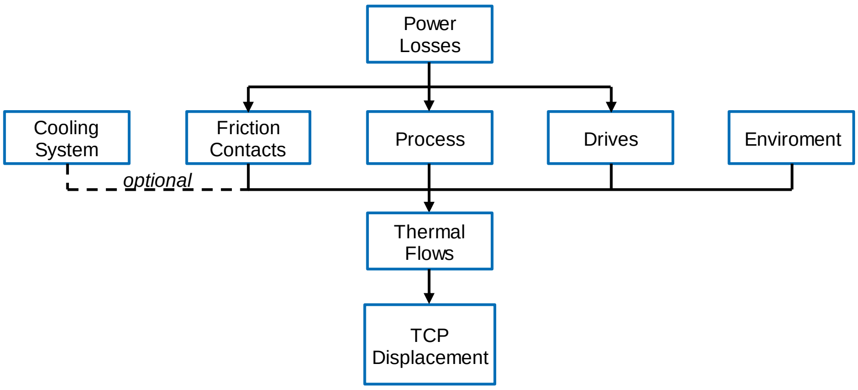


Figure 3: Thermo-energetic functional chain and correction approaches [5]

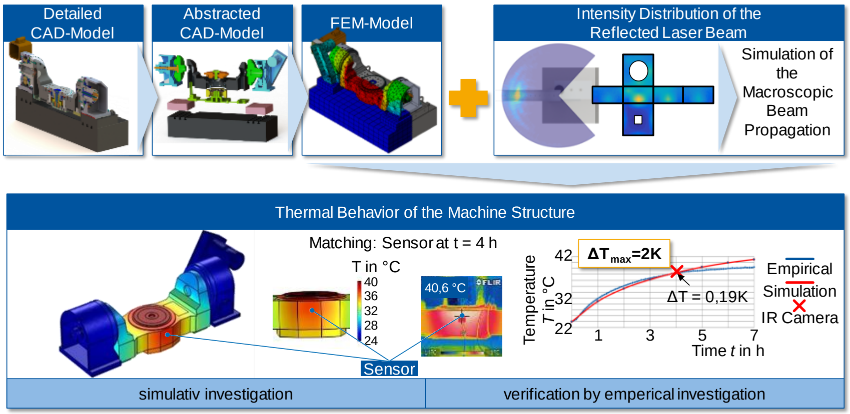
All the simulations have to be verified by measurements that only reflect the considered influence. As their final goal is to predict the total TCP deviation, they have to be assembled afterwards. But to be able to verify the superposition of the different predictions, a global measurement of the effect is necessary.

The measurement is performed on a Machine with a CAFYXZ axis setup. The measurement and compensation of the linear kinematic chain is already a research topic [15]. To be able to compensate five-axis machine tools this paper focuses on the rotary axis. As a first step the thermal drift of the C axis is investigated.

As mentioned before, a potential cause for a drift of the C axis can be a laser based machining process. Within the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” at RWTH Aachen, a Multi Technology Platform (MTP), a five-axis milling machine with integrated laser processing units, has been build up and investigated. It is essential to know all single kinds of thermal influences, e.g. the process, for a prediction of the thermal-elastic behavior of the machine structure. Besides the common effects of heat transfer, conduction, convection and radiation the knowledge about the behavior of the electromagnetic beam (laser beam) is important. In an automated production system, such as the DMG Mori Lasetec 65, laser based machining can take up to more than 50% of the total machining time which results in a lot of laser power being induced into the workspace. Considering an absorption coefficient of steel of around 50% of steel there is still some power reflected from the process towards the machine structure, for example the table. So the laser beam is part of the influence evolving a drift of the machine structure respective components and the fraction of the beam leaving the process area needs to be investigated in order to predict the thermal-elastic behavior of such machine tools already in the design phase. This fact has been investigated by Breitbach [16;14;17].

3 Laser Beam Propagation

Initially a laser beam is generated by a laser source, then guided and focused by an optical processing unit and used to heat up material as needed in the process zone. The amount of energy striking the material can be then divided into fractions that are absorbed, reflected or transmitted. The absorbed energy, in combination with the area and time of impact, determines the type of interaction in the process zone – from heating to deep welding or vaporizing. All types of the mentioned interactions only use fractions of the laser beam. Some energy is reflected in the process area and absorbed somewhere else in the workspace. To predict the amount of energy being absorbed, a simulation of the beam propagation in the macroscopic workspace is indispensable. The common procedure, shown in Figure 4, to predict the behavior of machine structures in the design phase is based on a 3D-CAD model of the desired object. The model is usually abstracted to reduce calculation time and increase the mesh quality by eliminating e.g. phases and holes.



Source: WZL, Peiseler

Figure 4: Procedure to simulate the thermal behavior of machine structure due to laser machining

In the case of simulating the laser beam path post process in the macroscopic machine workspace the surface of the involved structure is crucial because the reflective behavior strongly depends on the surface quality. A method and tool to create a surface without measuring a real one is introduced by Frekers et. al. and can be used in the simulation model. [18] Figure 5 shows the setup of the generated surface and the schematic influence of different surface conditions. The simulation excludes the dynamic simulation of the process spot itself and focusses on the mechanisms post process where there is only a small influence of the laser beam on the surface quality.

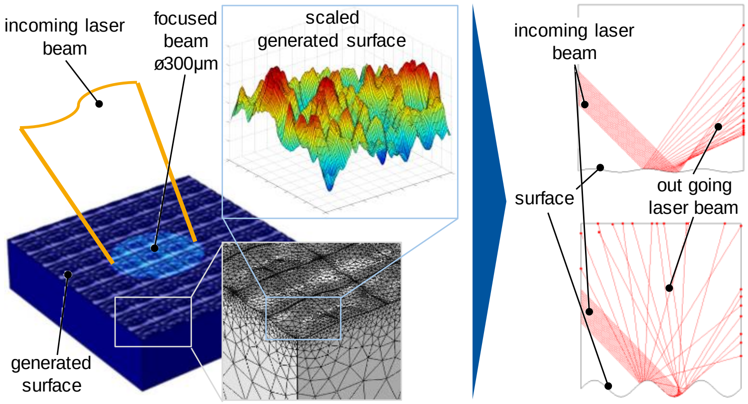


Figure 5: Mechanisms of post process reflection depending on the surface quality

Summing up the quality of the surface determines the degree of scattered reflection and thus the distribution of the beam on the following surfaces. So for a reliable prediction of the thermal-elastic behavior due to the reflected laser beam it is necessary to understand the mechanisms of a single reflection as well as of multiple reflections in a self-contained space. Braunreuther has developed a measure arc which has been optimized to examine the single reflection of the laser beam. [19] Studies have been performed analyzing the influence of different surface qualities based on the material (steel, anodized aluminium and copper) in combination with different angles of impact and laser power. Figure 6 shows the principle results of the single and multiple reflections and the distribution of beam intensity on a sphere, for single reflection, and in a self-contained box, for multiple reflection at 300W laser power.

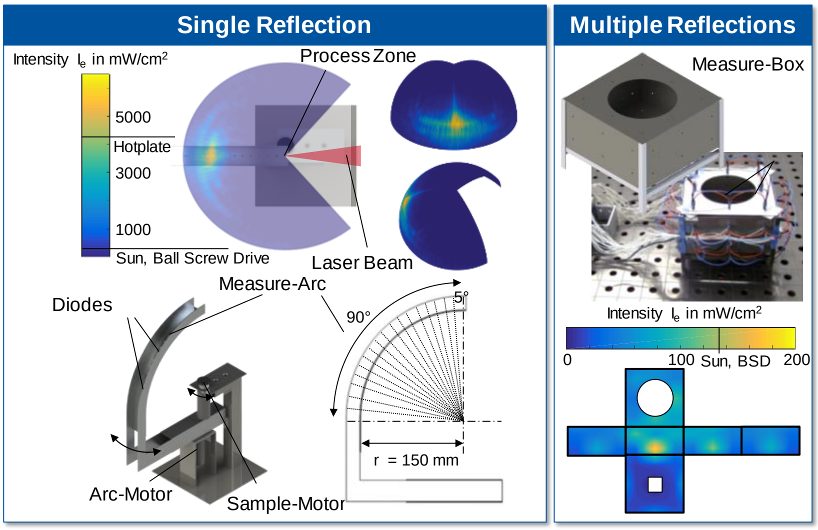


Figure 6: Single and multiple laser beam reflection

By integrating surface models in the simulation model for the macroscopic workspace a prediction of the propagation is possible. The output parameters of the beam simulation can then be used as input parameters for a thermal simulation and these parameters later for the determination of resulting mechanical distortions – the shift in axes - due to the isolated influence of the laser beam. The used procedure is shown in Figure 4 where the distribution of laser beam energy is substituted by two different heat sources on the surface in order to gain a verified thermal model to use for the assembled simulation models consisting of beam propagation simulation including the surface generation and the thermal distribution simulation followed by the mechanical deviation simulation. This way the deviation caused by the laser beam can be displayed. In order to receive the total deviations of the machine, the single simulations of the different influences, such as the laser beam, have to be joined in a combined simulation of the thermal behavior. The generated output parameters, the thermal distribution, then can be used to gain information of the total deviation, which also depends on physical parameters such as the coefficient of expansion. But since these coefficients are fluctuating there is an uncertainty in the simulation. In order to verify the deviation, it is necessary to use a measuring method which will be introduced in the following chapter.

4 The New Measuring Method

4.1 Introduction of the new measurement setup

The ISO 230-3 standard offers a common method to measure thermal drifts of machine tool main spindles. [20] The new measurement method uses this foundation and extends the capability of the standard mandrel measurement setup. To investigate modern five-axis machine tools, spindle and table axis deviation have to be measured. The new setup gives hints about multidimensional deformations of the machine table such as a crowned or a hollow surface. Therefore five mandrels are mounted on the machine table and the sensor mounting device is fixed in the spindle, Figure 7. All parts of a significant length are made out of Invar to reduce the thermal elongation of the parts. They are considered as thermally stable.

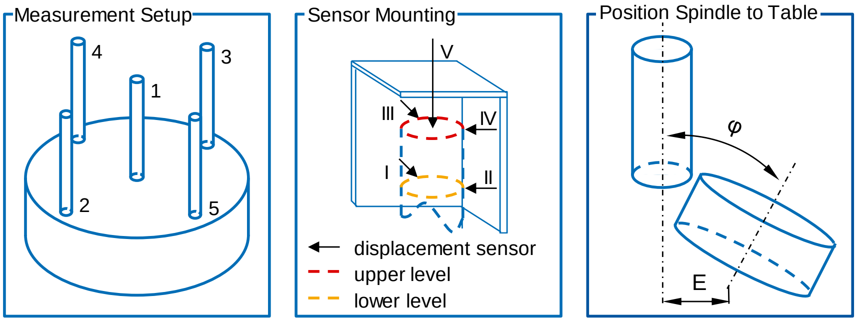


Figure 7: Measurement setup

The sensor mounting device five displacement sensors to determine the thermal lift of the spindle / table, angular deviations of the spindle by rotation of the sensor mount around the central mandrel, crowning or hollowing of the table by comparing the central mandrel angular deviation to the four outer ones and the drift of the rotational axis by rotation of the central mandrel in the sensor mount.

4.2 Measurement data analysis

All measurements aim at detecting thermal effects of the mechanical load. To assure a steady thermal state of the machine, all drives are controlled for at least 12 hours. In addition, the thermal errors have to be separated from the initial geometrical misalignments of the assembly. Therefore, all measurement results are rated relatively to the initial measurement by subtracting the first measurement results.

All measurements base on a rotation of the sensor mount around the mandrel. The result is a deviation plot over time, Figure 8, with the knowledge of the mounting situation of the sensors the time based plots of the four sensors can be allow to calculate the mandrels centres on the sensor level. Sensors on two levels help to calculate the angular deviation of the mandrels, Figure 7.

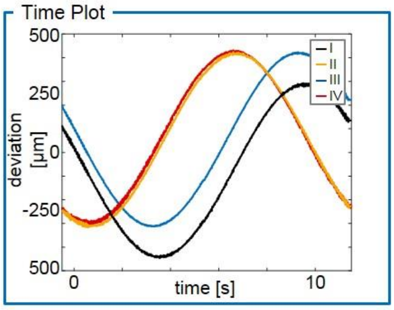


Figure 8: Example raw data plots

The next paragraph briefly describes the approach to determine a standard uncertainty for the measurement device after JCGM 100:2008 [21]. The mode for the evaluation is type A, therefore the same measurement has been performed 50 times. The estimation of the expectation value is in this case the arithmetic average of all observations and the variation is the quotient of the experimental variance and the square root of the number of observations.

To calculate the expanded uncertainty the standard uncertainty is multiplied with the coverage factor k = 2.05 which leads to a fraction of 95.45% for 50 observations. This leads to a maximum deviation of the mandrel's centre of $\sigma_{k=2}$ = 0,8 µm per direction.

5 Conclusion and Outlook

The method to simulate the shift of axes due to the isolated influence of electromagnetic radiation caused by laser based machining in a laser integrated machine tool has been introduced. The need for detailed consideration of the surface quality of affected machine structures is essential for a prediction of the beam propagation as input parameter for following simulations of the thermal distribution and the mechanical distortion. Further more a verified thermal model as part of the complete simulation model, that still has to be assembled, has been shown as well as the empirically gained data of single and multiple reflections of the laser beam.

The uncertainties of the simulations of the single influences have to be determined in detail and considered in the next steps. Further investigation focuses on the detailed simulation of the single and multiple reflection of the laser beam taking the uncertainty of the experimental measures as well as the simulations in account. Also a verification by already undertaken experimental investigations have to be made. These parameters then will be used with the already verified model of a 2 axes turn swivel table in order to receive the thermal distribution due to the laser beam.

The measurement method allows to verify the assembly of different simulations of the thermal drift of a rotational machine tool axis. The measurement uncertainty is in the sub micron range, what is precise enough for these measurements. Next development steps are a full measurement of a machine table.

Acknowledgement

The authors would like to thank the German Research Foundation DFG for the financial support. The represented findings result from the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” and from the subproject B06 “Investigation of Components and Assembly Groups” of the special research field CRC/Transregio 96.

References

[1] - Mayr, J.: Beurteilung und Kompensation des Temperaturganges von Werkzeugmaschinen. Diss. ETH Zürich. 2009

[2] - Weck, M.; Brecher, C.: Messtechnische Untersuchung und Beurteilung, dynamische Stabili-tät. In: Werkzeugmaschinen und Fertigungssys-teme - Bd. 5, 7. Auflage, Berlin: Springer. 2006

[3] - Mayr, J.; Jedrzejewski, J.; Uhlmann, E.; Donmez, M.A.; Knapp, W.; Härtig, F.; Wendt, K.; Moriwaki, T.; Shore, P.; Schmitt, R.; Brecher, C.; Würz, T.; Wegener, K.; Thermal Issues in Machine Tools, CIRP Annals – Manufacturing Technology, 61 (2) (2012), pp. 771–791

[4] - Weck, M.; Brecher, C.: Werkzeugmaschinen - Konstruktion und Berechnung. 8. Aufl., Berlin: Springer. 2006

[5] - Brecher, C.; Wennemer, M.; Fey, M.: Tempera-turstabile Werkzeugmaschinen. In: Wt Werk-stattstechnik online. Jg. 104. 2014

[6] - A. Wissmann, Steuerungsinterne Korrektur thermisch bedingter Strukturverformungen von Bearbeitungszentren. In: Ergebnisse aus der Produktionstechnik, Diss. RWTH Aachen. 2014

[7] – C. Wenzel, J. Flore, M. Klatte, Direkte Messung lokaler Verlagerungen mit strukturintegrierter Sensorik als Voraussetzung für Korrektur und Kompensation, SFB/TR-96, 1. Kolloquium SFB/TR96, Thermo-Energetische Gestaltung von Werkzeugmaschinen. 2012

[8] - Herzog, R.; Riedel, I.: Sequentially optimal sensor placement in thermoelastic models for real time applications. Optimization Engineer, Volume 16, Issue 4. 2015

[9] - C. Kral, A. Haumer, S. Bin Lee, A Practical Thermal Model for the Estimation of Permanent Magnet and Stator Winding Temperatures, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 1. 2014

[10] - Weber, J.; Weber, J.; Shabi, L.; Lohse, H.: Energy, Power and Heat Flow of the Cooling and Fluid Systems in a Cutting Machine Tool, Procedia CIRP Volume 46. 2016

[11] - A. Frias, A. Kedous-Lebouc, C. Chillet, L. Albert, L. Calegari, O. Messal, Loss Minimization of an Electrical Vehicle Machine Considering Its Control and Iron Losses, IEEE TRANSACTIONS ON MAGNETICS, VOL. 52, NO. 5. 2016

[12] – Brockmann, M.: On the Use of Potential Theory for Thermal Modeling in Metal Cutting. In: Ergebnisse aus der Produktionstechnik, Diss. RWTH Aachen. 2016

[13] - Klocke, F.; Wrobel, C.; Rasim, M.; Mattfeld, P.: Approach of characterization of the grinding wheel topography as a contribution to the energy modelling of grinding processes, Procedia CIRP 46. 2016

[14] - Brecher, C.; du Bois-Reymond, F.; Breitbach, T.; Do-Khac, D.; Bäumler, S.; Fey, M.; Lohse, W.: Qualifying Multi-Technology Machine Tools for Machining Precision. In: CIRP Journal of Manufacturing Science and Technology. 2015

[15] – Brecher, C.; Wennemer, M.; Fey, M.: Control-Internal Compensation Algorithm for thermally induced volumetric Tool-Center-Point Deviations. Laser Metrology and Machine Performance XI, LAMDAMAP 2015, University of Huddersfield /West Yorkshire, UK. 2015

[16] – Breitbach, T.: Auslegung und Bewertung laserintegrierter Bearbeitungszentren. In: Ergebnisse aus der Produktionstechnik, Diss. RWTH Aachen. 2014

[17] – Brecher, C.; Özdemir, D.: Integrative Production Technology - Theory and Applications. Berlin: Springer. 2016

[18] – Frekers, Y.; Vieler, S.; van Buren, S.; Deppermann, M.; Kneer, R.: Determination of thermal contact resistance coefficients through thermos-mechanical simulation. In: Proceedings of the 15th International Heat Transfer Conference, IHTC-15, Kyoto, Japan. 2014

[19] - Braunreuther, S.: Untersuchungen zur Lasersicherheit für Materialbearbeitungsanwendungen mit brillianten Laserstrahlquellen. Herbert Utz, München. 2014

[20] ISO 230-3 (August 2007). Prüfregeln für Werkzeugmaschinen - Teil 3: Prüfung des thermischen Verhaltens

[21] JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (ISO/IEC Guide 98-3:2008)