Temperature Measurements and Heat Partitioning in Machining Processes

J. Sölter, R. Frohmüller and H. Wirbser

Abstract Temperature measurements were of special interest in the Priority Programme (SPP) 1480 of the Deutsche Forschungsgemeinschaft (DFG). Therefore the working group on temperature metrology was established. Calibration setups for (1) contacting thermometers developed at the ITT Karlsruhe and (2) radiation thermometers developed at the IFQ Magdeburg were utilized in the projects of the SPP 1480 to provide comparable high quality temperature measurements. Additionally, heat partition data was collected from the involved projects and aggregated by applying the dimensionless thermal number known from orthogonal cutting. Although theoretical calculations qualitatively agree with results from the experiments further research is needed to predict the heat partition to the workpiece for industry relevant processes.

1 Introduction

The thermal impact of machining processes is often critical regarding the achievable geometric workpiece accuracy, especially if coolants are not applied. One reason is the accumulation of heat leading to inhomogeneous temperature distributions in the workpiece. As a result the effective material removal in the process deviates from the nominal material removal given by the machining parameters. Other factors such as the machine tool accuracy or the generation of a locally

J. Sölter (✉)
Department of Manufacturing Technologies, Foundation Institute of Materials Science, University of Bremen, Badgasteiner Str. 3, 28359, Bremen, Germany
e-mail: soelter@iwt.uni-bremen.de

R. Frohmüller
Institut für Fertigungstechnik und Qualitätssicherung, Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany

H. Wirbser
Institut für Technische Thermodynamik, KIT—Karlsruher Institut für Technologie, Kaiserstraße 12, 76131 Karlsruhe, Germany

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Table 1 Machining Processes analyzed in the SPP 1480 and applied temperature measurement techniques

technique / process	hobbing	drilling	turning	milling	grinding
thermocouple		IFW, wbk, ISF, IIW	wbk, FBK, WZL	ISF, IFW, iwb	ISF
resistance thermometer	IfQ				
pyrometer	IfQ	IFW, wbk	wbk, WZL	iwb	
infrared camera	IfQ	IFW, wbk, ISF, IIW	IWF, wbk, WZL	IFW, iwb	

plastically deformed surface layer leading to residual stress in the whole workpiece also contribute to size and shape deviations of the workpiece.

In order to be able to quantify the thermal impact of the machining processes analyzed within the framework of the Priority Programme (SPP) 1480 of the Deutsche Forschungsgemeinschaft (DFG), temperature measurements were at the core of the experimental work of the involved projects (Table 1). The project groups supported each other in periodic meetings of the working group on temperature metrology in which mainly the temperature measurement setups and the results were presented and discussed.

2 Objectives

Temperature measurements within the single projects of the Priority Programme mainly aimed at determining the heat partition to the workpiece for different process conditions as input for the process simulations and/or on providing validation data for process simulations. As a result, the main objective of the working group on temperature metrology was to support the projects in their activities and achieve comparable high quality temperature measurements. Moreover, the working group sought to aggregate the heat partition data for different machining processes determined at the laboratories involved in the Priority Programme in a unified way.

Based on the state of the art in temperature measurements, standardized calibration setups and procedures for the utilized measurement techniques were developed and applied. The measured temperatures were then used to determine the heat partition to the workpiece for different processes and process conditions.

3 Temperature Measurement Techniques

Thermally driven mechanisms play a major role in machining processes. Elevated temperatures promote tool wear and affect the generation of material modifications such as residual stress, phase transformations and crack formation as well as the geometric accuracy of the workpiece due to thermal strains. Consequently, temperature measurements in machining have a long history. The first work cited in literature dates back to 1798 [1]. Count Rumford conducted calorimetric experiments in which he estimated the heat generated during boring brass cannons by comparing it with the heat from burning wax candles. Temperature measurement methods have considerably developed since that time. In most machining applications today contacting thermometers such as resistance thermometers and thermocouples as well as radiation thermometers, e.g. pyrometers and infrared cameras are utilized. Other temperature measurement techniques, such as spectroscopic measurements and those that are based on thermophysical processes will not be presented here but are discussed in more detail in [2].

3.1 Contacting Thermometers

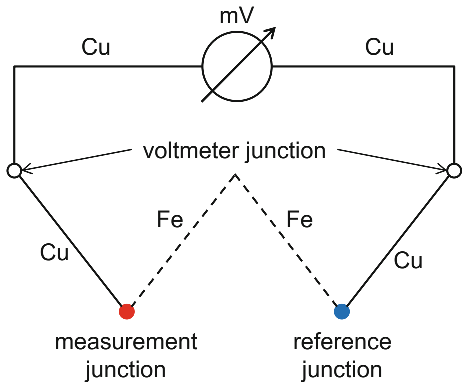
3.1.1 Resistance Thermometers

The temperature dependence of the electrical resistance is utilized to determine the temperature with so-called resistance thermometers. With an appropriate measurement setup temperatures can be determined with an accuracy of 10^{-4} K. For resistance thermometers pure metals, in particular platinum and nickel, are preferred due to their well reproducible temperature dependent electrical resistance. For this reason metal alloys are not suitable. Moreover, the advantage of metal resistance thermometers lies in their high accuracy. Platinum is the most common material for resistance thermometers. It has a high chemical resistance and different resistor types such as wire, layer or foil resistors are comparatively easy to produce from platinum. “While they are inexpensive, accurate and relatively easy to use, comparatively speaking, they are relatively large, have long time constants and are limited in temperature range” [3].

3.1.2 Thermocouples

The working principle of a thermocouple (TC) is the Seebeck effect. If an isotropic homogeneous metal, e.g. a copper wire, is subjected to a temperature gradient a diffusive charge carrier transport will generate an electric field that counteracts the diffusion. The electric field is proportional to the temperature difference with the Seebeck coefficient being the constant of proportionality. The Seebeck coefficient is

Fig. 1 Circuit diagram of a thermocouple



a material property. If two wires composed of dissimilar metals, e.g. copper and iron, are joined at both ends and one junction is heated (measurement junction), the thermal voltage, i.e. the difference of the electric fields in both wires, causes a current to flow in the thermoelectric circuit. The thermal voltage can be measured if the circuit is broken and a high resistance voltmeter is connected to the leads (Fig. 1). In order to calculate temperatures from the voltage at the measurement junction the second (reference) junction has to be kept at a constant known temperature, e.g. by immersing it into an ice bath (0 °C). Moreover, the measured thermal voltages have to be converted to a corresponding temperature. For this purpose a thermocouple has to be calibrated before the actual temperature measurements (Sect. 4.1).

Each junction between two dissimilar metals in a circuit contributes to the thermal voltage and potentially leads to erroneous temperature measurements. Measurement errors can be avoided either by using the same material for the thermocouple wire and the voltmeter leads as shown in Fig. 1 (Cu). Also dissimilar metals can be used but then the voltmeter junctions have to be at the same temperature.

Depending on the materials used in TCs temperatures from −200 °C to almost 2,000 °C can be measured. Most common in machining applications is the type K (NiCr-Ni) thermocouple with a temperature range from −200 °C to 1,300 °C. TCs are "(1) relatively low cost; (2) rugged; (3) versatile and available for many temperature ranges; (4) reasonably stable and reproducible; (5) subject to relatively low uncertainty when used as designed; and (6) fast responders, depending on size" [3]. Nevertheless uncertainties in TC measurements are associated with cold work of the thermocouple wires, with temperature gradients at the measurement junction and with an inadequate temperature control of the reference junction.

3.2 Radiation Thermometers

Planck's law describes the dependence of the spectral emissive power on the temperature of a blackbody. A blackbody absorbs all incident radiation regardless of wavelength and direction. It is an ideal emitter that emits as much as or more energy than any other body at the same temperature and it radiates the energy isotropically (diffuse emitter). When integrated over all wavelengths Planck's law becomes the Stefan-Boltzmann law which states that the total emitted power per unit area of a blackbody is proportional to the fourth power of its temperature. This is the basis for all radiation thermometers: measuring the emitted power can be directly linked to the temperature of a body. However, sources of error in radiation measurements mainly arise from deviations of real bodies from a blackbody. Especially metal surfaces show a strong dependence of the emissivity (= absorptance) on the wavelength and the temperature. Also, the surface properties strongly affect the emissivity. Additionally, the emission characteristics depend on the angle by which the electromagnetic waves are emitted from the surface. From the above mentioned it can be concluded that the emissivity is not solely a surface characteristic, it is the fraction of the total emitted radiation from a technical surface to the radiation emitted by a perfect blackbody at the same temperature. Thus, emissivity values range between zero and one.

Other effects contributing to measurement errors are background radiation and the transmissivity along the optical path from the source, i.e. the surface, to the detector of the thermometer including the lens system. Due to the manifold influences a mathematical description of the emissivity of technical surfaces in closed form is not possible. Thus, a calibration, i.e. an experimental determination of the emissivity, is the central task before conducting temperature measurements with radiation thermometers.

3.2.1 Radiation Detectors

Quantum detectors can be used as a receiver of the incident radiation. These detector types basically count photons and are made of semiconductor materials. The energy of the photons is absorbed and lifts electrons from the valence band to the conduction band of the semiconductor giving rise to a photoelectric current that can be measured.

In another detector type the absorption of the incident radiation leads to a temperature increase of the detector material. The temperature increase causes a change of the electrical resistivity (bolometer) similar to resistance thermometers. Thermopiles are composed of several thermocouples attached to an absorbance material at their "hot" junction. The absorbance material is heated up by the incident radiation and due to the temperature gradient relative to the "cold" junction of the thermocouples a thermoelectric voltage can be measured. The thermocouples are often connected in series aiming at an increase of the thermoelectric voltage, therefore enabling a more sensitive measurement of temperature differences between the "hot" and the "cold" junction. Both bolometers and thermopiles are manufactured by thin-film technology.

3.2.2 Types of Radiation Thermometers

Depending on the wavelength range that is utilized to measure the temperature, radiation thermometers can be classified as follows [3]:

- Total radiation thermometers should collect 90% of the radiation from a surface. This is achieved by maximizing the collection cone and the wavelength band. According to Planck's law the spectral emissive power becomes very small for low temperatures. For this reason total radiation thermometers are especially useful in this temperature range (<50 °C).
- Spectral band thermometers (single color pyrometers) and imagers collect radiation from a small wavelength band of the radiation. From Planck's law it follows that the peak wavelength where the maximum spectral emissive power occurs is shifted to lower wavelengths when the temperature increases. Thus, the detector should be adapted to the wavelength band around the peak wavelength. Since the emissivity of the surface to be measured varies with both, wavelength and temperature, a calibration is inevitable for reliable temperature measurements with single color pyrometers. Spectral thermometers are also band thermometers but with a very limited bandwidth between two and five percent of the wavelength of interest.
- Ratio thermometers, often called two-color pyrometers, collect radiation at two different wavelengths aiming to eliminate the influence of emissivity on the temperature measurement. The main prerequisite for measurements with two-color pyrometers is that the surface to be measured behaves like a gray body, i.e. that the emissivity of both wavelengths is identical. As a consequence the conditions under which ratio thermometers can reliably be applied without being calibrated depend on the a priori knowledge of the emissivity characteristics of the surface. "In fact, for materials where emissivity varies with wavelength, use of the ratio thermometer would be in question" [3].

4 Calibration of Thermometers in the Priority Programme

4.1 Contacting Thermometers

For the calibration of contacting thermometers in the projects of the Priority Programme a setup at the ITT Karlsruhe was developed. It consists of a thermostat in which a copper core is heated up to preset calibration temperatures (Figs. 2 and 3). The "true" temperature is measured with a calibrated precision platinum resistance thermometer PT 25 (25 Ω at 0 °C, Rosemount). A high resistance digital multimeter (DMM) and a constant current source are needed for the measurement with the precision thermometer in a 4-wire sensing setup. It is important to calibrate each temperature sensor, either a resistance thermometer or a thermocouple, as part of the complete measuring chain that will be used in the experiments.

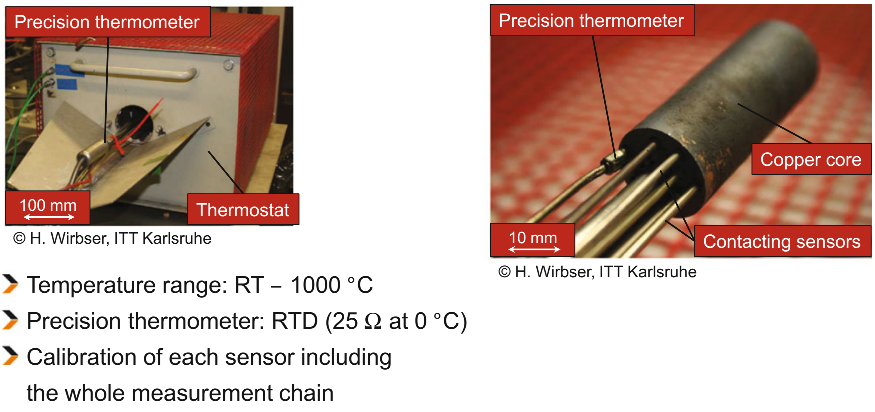


Fig. 2 Calibration setup for contacting thermometers (ITT Karlsruhe)

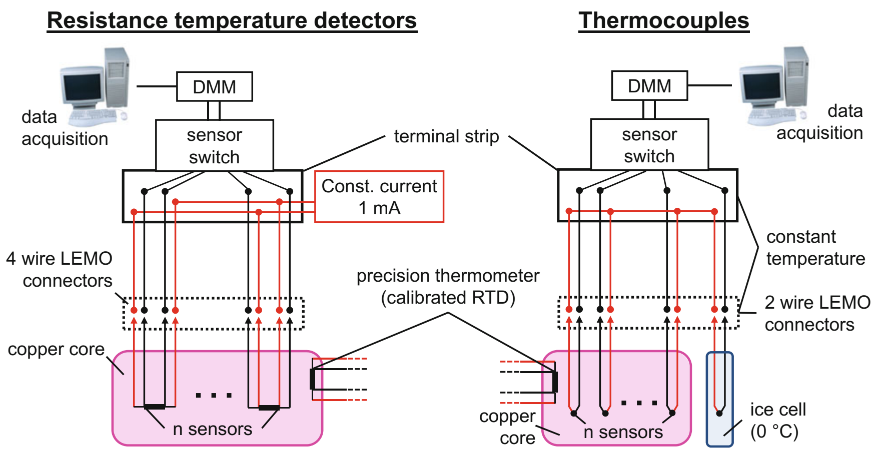


Fig. 3 Circuit diagram of the calibration setup for contacting thermometers (ITT Karlsruhe)

4.1.1 Resistance Thermometers

Resistance thermometers should be connected with 4-wire LEMO connectors in series (not more than ten) to avoid warming by the measuring current (Fig. 3, left). For selecting the different resistance thermometers in the measuring chain a multiplexer is needed. If the measuring chain consists of more than ten sensors a constant current source and a temperature compensated precision resistor should be used. By measuring the voltage drop at the precision resistor, the sensor current can be determined. The resistance (voltage drop) at each sensor is measured in a 4-wire sensing setup. LEMO connectors should also be used to connect the sensors to the multiplexer.

4.1.2 Thermocouples

It is strongly recommended to design the calibration setup in the same way as the measurement setup. This means in particular that the measuring instruments and the thermocouples should be identical and should be arranged to each other in the same way. Also, the surrounding conditions during calibration and the actual measurement should be comparable in order to avoid erroneous temperature measurements by additional thermal voltages originating from junctions between thermocouples and the digital multimeter or voltmeter. Thermocouples and voltmeter should be connected with gold-plated LEMO connectors. Moreover, the connections should be kept on a constant temperature to minimize measurement uncertainties. The use of compensation leads is recommended for connecting reference and measurement junction, e.g. when they are far away from each other. Compensation leads have the same thermo-electrical behavior as the thermocouple wires. This assures that no additional thermal voltage is generated. Since self-heating of the voltmeter might also affect the measurement it should be switched on in advance, so that a stationary temperature of the instrument can be assured before the calibration or measurement starts.

The use of class 1 K-type thermocouples is recommended due to the linearity of the thermal voltage in the temperature range between 0 °C and 1,000 °C (Seebeck coefficient of 41 μV/°C). Additionally, an ice cell can be used as a reference junction (0 °C, Fig. 3, right).

4.1.3 Calibration Procedure

In a comparative calibration as shown in Fig. 3 the sensor signal (resistance or voltage) is plotted over the temperature readings of the precision thermometer. The signal of each sensor at a preset temperature will be read at least five times within a defined time span. By applying the method of least squares a second order polynomial is fitted to the measured output signals of each sensor. The calibration starts with the lowest "true" temperature within the temperature range of interest and ends with the highest "true" temperature. In a second cycle the temperature is decreased to the lowest temperature. This procedure should be conducted two to three times leading to a set of three model parameters for each thermocouple and for each heating or cooling cycle. From these the preliminary model parameters are calculated. In a final step they are used to compute the temperatures from the sensor signals within the temperature range during calibration which are then compared with the true temperature readings from the precision thermometer.

4.2 Radiation Thermometers

4.2.1 Calibration Setup

At the IFQ Magdeburg a calibration setup was developed [4] was developed and provided to calibrate the radiation thermometers used in the projects of the Priority Programme (Figs. 4 and 5).

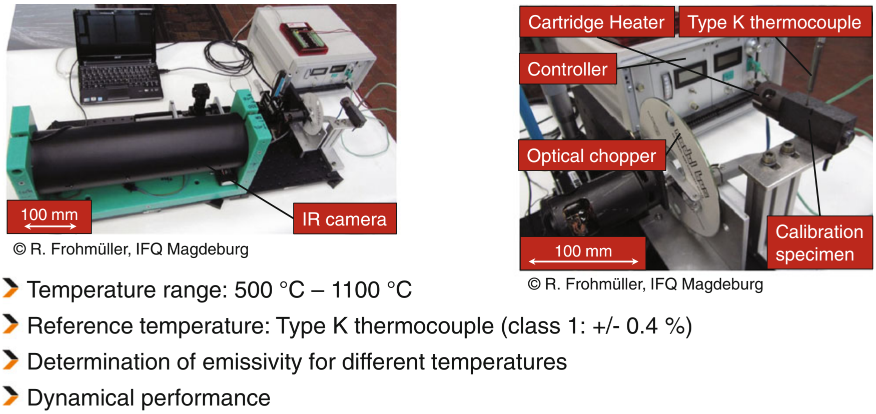


Fig. 4 Calibration setup for radiation thermometers (IFQ Magdeburg)

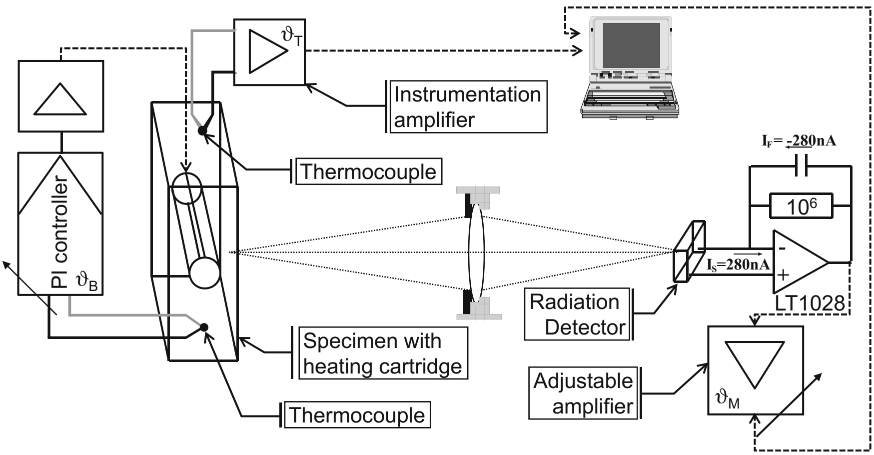


Fig. 5 Circuit diagram of the calibration setup for radiation thermometers (IFQ Magdeburg)

The main component of the calibration setup is a workpiece material sample in which a heating cartridge connected to a PI-controller is inserted. For a reliable calibration it is important that the calibration sample

- is made of the same material as the specimens for the temperature measurements and
- that it is premachined in the same way.

Otherwise the surface characteristics may differ and thus, the calibration might lead to erroneous temperature measurements. The PI-controller assures that the sample is heated up to a preset steady-state-temperature and minimizes temperature gradients within the sample or on its surface. A steady state is reached if the temperature on the surface (true temperature ϑ_T) is the same as in the bulk (ϑ_B).

It is advisable to start with the highest temperature of the calibration range since at higher temperatures oxidization of the surface might occur and permanently change its radiation characteristic. Thus, starting with the highest calibration temperature assures that the surface radiation characteristic does not significantly change during calibration. The true temperature ϑ_T is measured on the surface of the heated sample with a class 1 K-type thermocouple.

4.2.2 Calibration Procedure

When the radiation thermometer is properly aligned to the specimen the measured temperature ϑ_M can be compared to the true temperature. The emissivity of the thermometer is adjusted starting with the highest possible value (1.0) until ϑ_M equals $\vartheta_{T.}$ Then the emissivity for the second highest temperature is calibrated in the same way and so forth. The temperature steps along the calibration curve should adaptively be changed depending on the emissivity change between two temperatures. Two different approaches are feasible to determine emissivities between adjacent calibration temperatures: (1) the complete calibration curve is fitted by an appropriate function over the analyzed temperature range or (2) emissivities are determined by a stepwise linear interpolation between the sampling points of the curve. The actual temperature measurements will be conducted with an emissivity of 1.0. Then the temperature dependent emissivity is utilized to (iteratively) correct the temperature measurements a posteriori. An example for a temperature dependent emissivity of an infrared camera applied in drilling 42CrMo4 samples and the effect of the emissivity correction on the resulting temperature field is shown in Fig. 6.

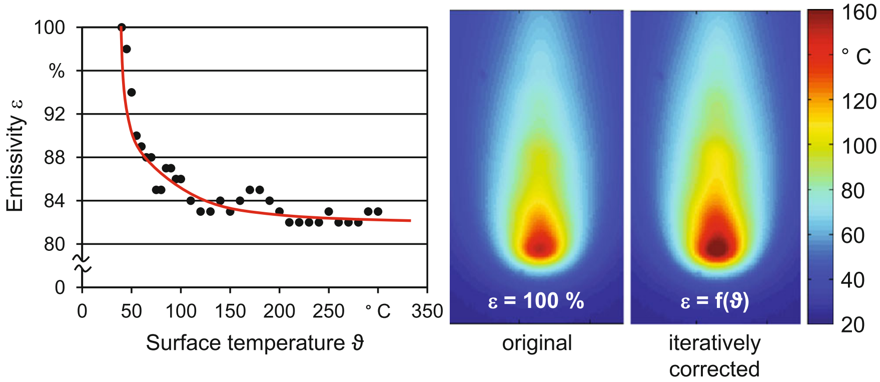


Fig. 6 *Left* temperature dependent emissivity in drilling; *right* corrected temperature field ([5], IWT Bremen)

5 Temperature Measurement Setups and Heat Partitioning

In the projects of the SPP 1480 workpiece temperature measurements were mainly conducted to provide input and validation data for the process simulations. Depending on the project temperatures were measured comparatively far off the chip formation zone making the measurements less error prone. In the following selected measurement setups will be presented for thermocouples and infrared cameras. In the second subsection the results on the heat partition to the workpiece for dry machining processes analyzed in the Priority Programme are presented and discussed.

5.1 Selected Temperature Measurements Setups

5.1.1 Thermocouples

In order to determine the total heat flow to the workpiece during turning of AlSiC metal matrix composites, the temperature increase of the whole workpiece was measured with thermocouples at the FBK Kaiserslautern (Fig. 7). For this purpose a telemetric data acquisition was attached to the workpiece. The energy dissipating to the workpiece can be calculated from the mass of the workpiece, the specific heat of the workpiece material and the measured temperature increase. The total process energy that is needed to finally determine the heat partition to the workpiece can be calculated from the cutting power and the process time.

In a milling setup at the IFW Hannover workpieces were equipped with K-type TCs along the milling path at different distances to the chip formation zone (Fig. 8).

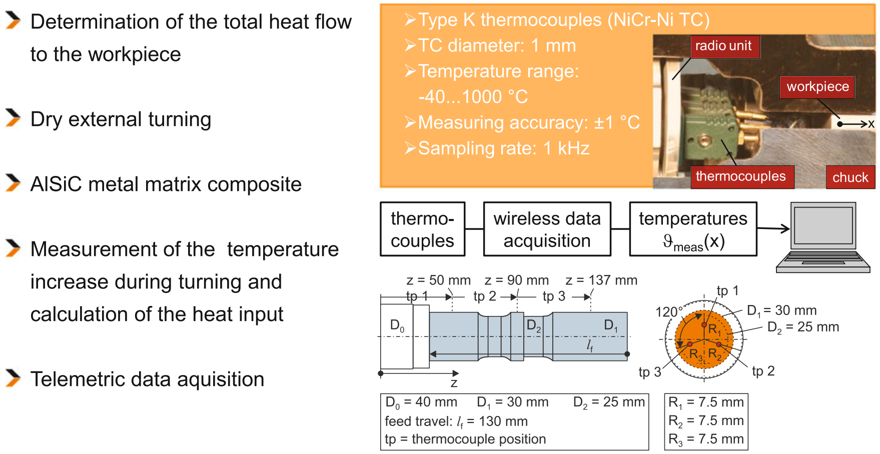


Fig. 7 Telemetric data acquisition for thermocouple measurements in external turning (FBK Kaiserslautern) [6]

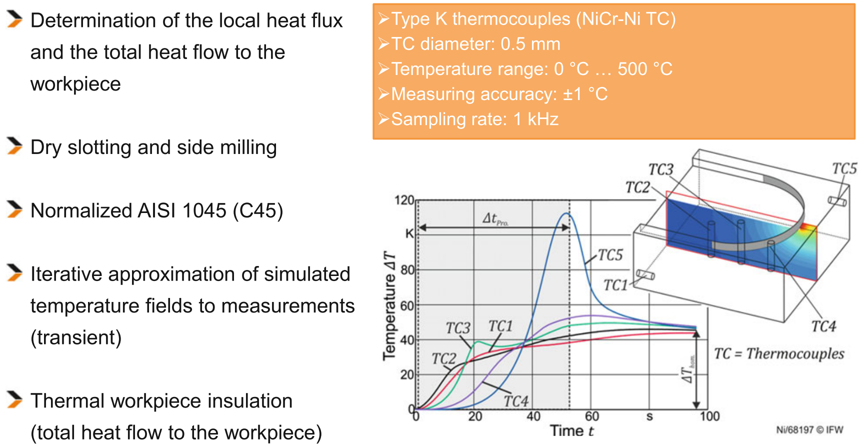


Fig. 8 Thermocouple measurements in milling (IFW Hannover) [7]

Additional TCs were positioned in two corners of the workpiece that was thermally insulated. With this setup the total heat flow to the workpiece could be experimentally determined (mean temperature increase at all TCs). By adjusting milling simulations until simulated and measured transient temperatures at the TCs one, two and three agree, also locally the heat dissipation to the workpiece at the maximum uncut chip thickness can be identified. The heat partition can be calculated by dividing the total heat that dissipated to the workpiece during the milling process by the total milling energy.

5.1.2 Infrared Cameras

The workpiece temperature distribution in milling was measured in a plane orthogonal to the working plane in a setup at the IWT Bremen (Fig. 9). In order to prevent chip collisions workpieces were machined in down-milling and the camera lens was additionally shielded with pressurized air. The aim was to determine the heat partitioning along the cutting arc. This was achieved by varying the width of cut on four levels and by iteratively changing the heat flux to the workpiece in milling simulations until simulated and measured temperature fields were in agreement. The cutting power was approximated by the measured electrical spindle power.

In plunge-turning experiments at WZL and WSA Aachen measured temperatures were utilized as validation data for a multiscale turning model [9]. The temperature field was measured on a workpiece plane orthogonal to the working plane of the process (Fig. 10). A slotted plate prevented chips from colliding with the camera lens and limited the measurement area of the camera to a region close to the chip formation zone.

In a deep-hole drilling setup at the ISF Dortmund workpiece temperatures were measured on the external workpiece surface (Fig. 11). Temperature fields were used to determine the total heat flux to the workpiece and to determine the heat partition to the workpiece for different drilling parameters. This was achieved in an inverse heat transfer analysis in which thermal process simulations were iteratively adjusted until simulated and measured temperature fields agreed.

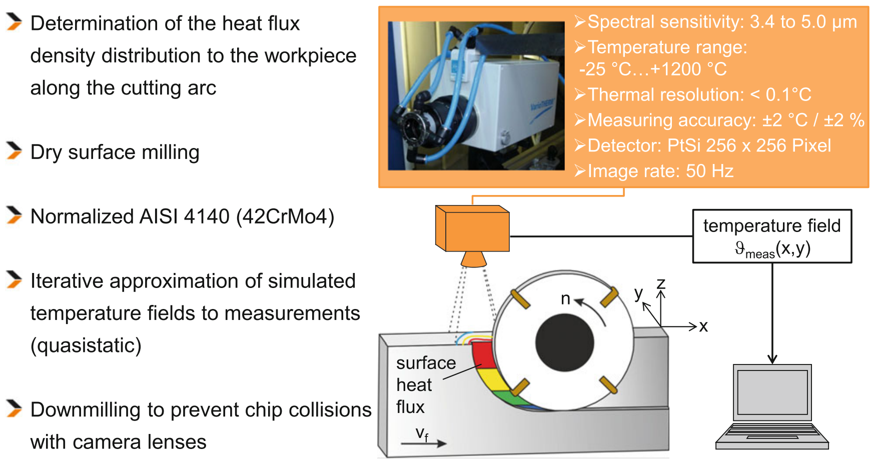


Fig. 9 Infrared camera measurements in milling (IWT Bremen) [8]

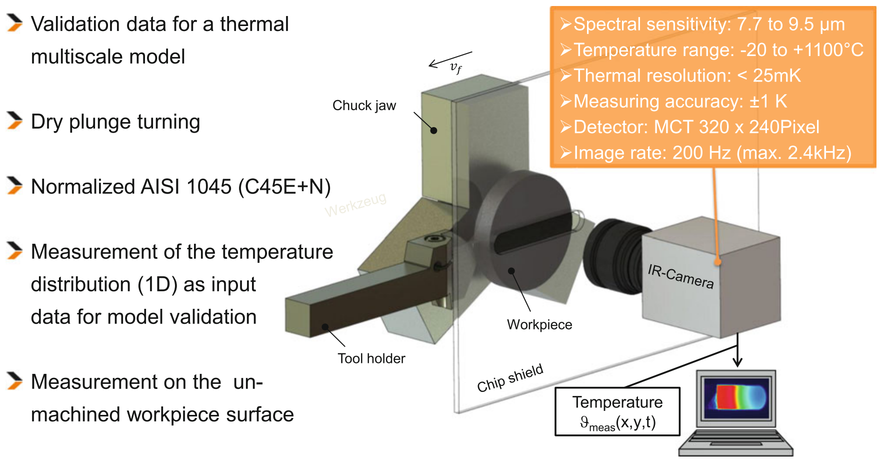


Fig. 10 Infrared camera measurements in plunge turning (WZL Aachen) [9]

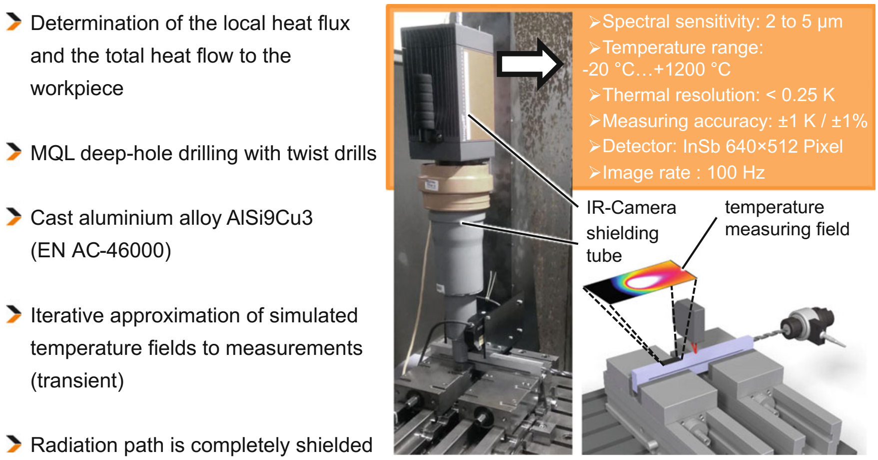


Fig. 11 Infrared camera measurements in deep-hole drilling (ISF Dortmund) [10]

5.2 *Heat Partition to the Workpiece*

It is well-known from theoretical works on the heat partitioning in orthogonal cutting that the heat dissipated to the workpiece predominantly depends on the dimensionless thermal number N_{th} (similar to the Péclet number). The thermal number in orthogonal cutting is the quotient of the cutting velocity times the uncut chip thickness and the thermal diffusivity of the workpiece material. Based on theoretical works of Komanduri and Hou [11] and experimental data from literature, the heat partition to the workpiece was numerically calculated and fitted by a

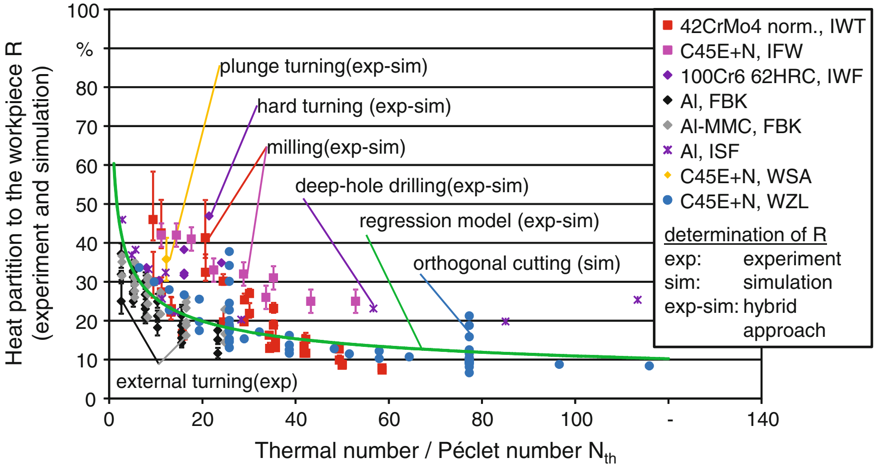


Fig. 12 Heat partition to the workpiece versus the thermal number for different dry machining processes

power law (Fig. 12, green line). It is obvious that finite element simulations of orthogonal cutting from Puls ([9], Fig. 12, blue circles) agree quite well as long as variations in the finite element (FE) model do not differ too much from the simplifying assumptions of [11]. Thermal numbers of 26 and 77 in the FE simulations comprise variations of (1) the width of the flank wear land, (2) the cutting edge radius and (3) the rake angle. Especially (1) and (2) lead to deviations from the analytical model whereas (3) does not significantly affect the FE-simulated heat partition to the workpiece.

The experimentally determined heat partitions follow the theoretical curve. However, depending on the process deviations can become quite high. In external turning the depth of cut was also varied in the experiments but it is not included in the thermal number. Thus, several heat partition values occur for identical thermal numbers. Similarly heat partition values determined in milling of 42CrMo4 increase with decreasing thermal numbers but partially strongly deviate from theoretical calculations. These experiments also included a variation of the depths of cut. Moreover, heat partition values for different uncut chip thicknesses were determined along the cutting arc for a given width of cut [8]. Thus, due to lateral heat flow in the workpiece, the heat partitions for different uncut chip thicknesses along the cutting arc affect each other.

The heat partition to the workpiece determined for milling C45 samples seems to be shifted to higher values compared to the theoretical curve. R values determined in hard turning and in plunge turning are also shifted to higher values. For thermal numbers below 30 heat partition determined in deep-hole drilling agrees reasonably well with theoretical values. However, for comparatively large N_{th} values the heat dissipating to the workpiece is higher in the experiment. Here, the N_{th} values correspond to very high feed rates (2.0, 3.0, 4.0 mm/rev). The deviation to theoretically calculated heat partition values might have been caused by additional friction effects, e.g. at the chisel edge, that become more pronounced if very high feed rates are utilized generating relatively high feed forces of up to 8 kN at a bore diameter of 10 mm [10].

It can be concluded that the theoretical description of the heat partition to the workpiece in orthogonal cutting can be applied to roughly estimate the heat partitioning in industry relevant processes. Especially the dependence on the feed velocity and the cutting velocity is represented by the approach based on orthogonal cutting theory. However, deviations are relevant if the process conditions deviate too much from the assumptions in theory, e.g. influence of tool wear, cutting edge radius as well as the depth of cut. The results indicate that the influence of the workpiece material is adequately described by the thermal diffusivity. The major mechanism that cannot be taken into account in the calculations based on Komanduri and Hou [11] is the removal of preheated workpiece material regions by subsequent cutting edge engagements. This should be analyzed in future research aiming at a more general description of heat partitioning that will then be applicable to industry relevant machining processes.

6 Summary and Conclusions

The working group on temperature metrology in the DFG Priority Programme 1480 was established to support the participating projects in their temperature measurement activities. The main goal of the working group was to assure comparable high quality temperature measurements. For this purpose a calibration setup for (1) contacting thermometers developed at the ITT Karlsruhe and (2) radiation thermometers developed at the IFQ Magdeburg were utilized. Temperature measurement setups from selected laboratories of the Priority Programme are presented and specific features of the setups and the applied approaches are discussed.

Based on the dimensionless thermal number N_{th} the heat partition data for different machining processes determined at the laboratories involved in the Priority Programme were aggregated in a unified way. Although qualitatively theoretical calculations based on orthogonal cutting describe the strong increase of the heat partition to the workpiece with decreasing thermal number, i.e. decreasing cutting velocity and/or decreasing uncut chip thickness correctly, quantitative results from industry relevant processes might be significantly different. This can be explained by the fact that the depth of cut, i.e. the uncut chip width and the feed velocity are not taken into account in the thermal number. Moreover, it is assumed that different process specific mechanisms contributing to the generation and dissipation of heat in machining processes, e.g. friction, are not adequately described by the definition of the thermal number as it is used in this publication. Therefore, it can be concluded that further research on heat partitioning should aim on incorporating effects that occur when industry relevant machining processes are to be described in a theoretical model of heat partitioning.

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