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Experimental Investigation of Thermal Boundary Conditions during Metal Cutting

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Abstract

Thermal boundary conditions in metal cutting are of major significance for the credibility of thermal models. Relevant boundary conditions need to be defined at the characteristic regions of metal cutting: the shear zone, the contact zone of chip and tool, the clearance face and the work piece surface. In this contribution, the experimental investigation of the thermal boundary conditions at these characteristic regions is presented. The boundary conditions were investigated by detailed analysis of infrared thermal images. Different materials and cutting parameters were investigated. From the investigation heat source strengths and heat partition ratios were yielded.

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Keywords: Cutting, Thermal Effects, Boundary Conditions

1. Temperatures and Heat in Metal Cutting

Temperatures evolving during metal cutting are of major importance for the efficiency of the cutting process. Increased temperatures can result in excessive wear the tool, i.e. costs, or cause thermal deflection of the work piece geometry [1]. The understanding of temperature fields and the resulting heat flux distribution is therefore a key enabler for optimized design and operation of cutting processes [2]. Despite the importance of the knowledge of thermal issues in metal cutting, temperature measurements require high experimental effort and are prone to errors. Therefore, computational models of thermal issues in metal cutting are of major significance.

While empirical models are by nature sensible concerning their numerical values, these type of models are mostly only valid for the regarded case. Models which are based on the fundamental physics, i.e. the partial differential equation of heat conduction, are transferable if a sound validation was conducted. The equation can be either solved by means of analytical computational models or numerical, i.e. simulative approaches.

For both types, the thermal boundary conditions, i.e. Neumann (i.e. prescribed gradient) or Dirichlet Condition (i.e. prescribed temperature value), at the characteristic regions of interest in metal cutting are of major importance. In particular the shear zone, friction zone and clearance face are regions of interest.

2. Experimental Investigation of Thermal Boundary Conditions

For the experimental investigation of typical thermal boundary conditions in metal cutting, cutting experiments on a broaching machine were conducted. The tests were carried out with an HSS broaching tool featuring a rake angle γ = 10 °and a cutting edge radius r_β = 5 µm. As cutting parameters, a cutting depth a_p = 40 µm and a cutting speed of v_c = 4 m/min was chosen. The test setup is shown in Fig.1. The temperature field was measured with an infrared camera and

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an additional two-color pyrometer focused on the rake face with a bore hole inside the work piece. The test material was Inconel 718, the cutting was conducted with dry conditions. Further details on the measurement method can be found in [3].

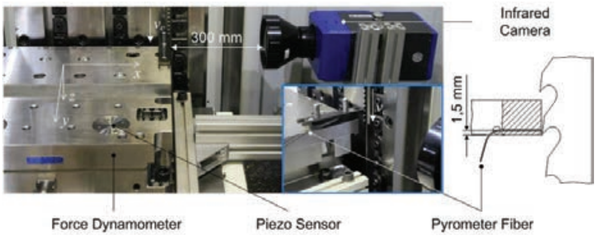

Fig. 1. Experimental Setup on Broaching Machine [3]

A typical infrared image of the trials is shown in Fig. 2. On the upper left-hand side, a contour plot depicting the temperature distribution in chip, tool and work piece is shown with the isotherms marked in different colors. On the upper right-hand side a mesh plot, i.e. the three-dimensional visualization of the temperature field can be found. As the thermal boundary conditions are defined by the gradient of the temperature along a space coordinate, the analysis of the mesh plot is a suitable tool for the analysis at the characteristic regions.

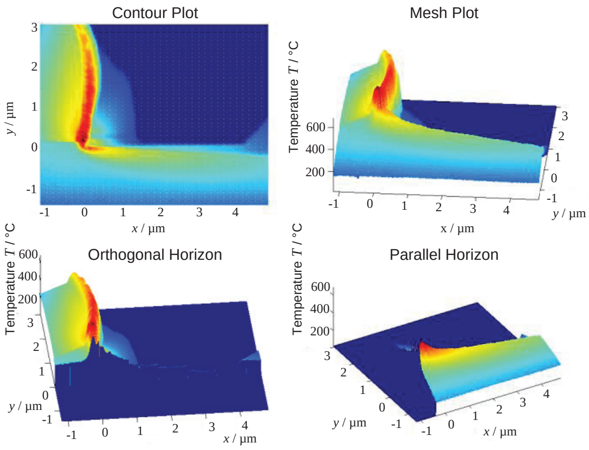

Fig. 2. Typical Infrared Image and Different Plot Types

For the analysis, the temperature slope was plotted against orthogonal and parallel planes of the mesh plot, as depicted in the lower part of the figure. The orthogonal horizon plot is thereby used for the investigation of the thermal boundary condition while the parallel horizon plot can be used for the temperature distribution at the appropriate characteristic region.

For the rake face, i.e. the region were the chip is pushed out and heat due to friction is generated, the parallel and orthogonal horizon plot is shown in Fig. 3.The different curves belong to the appropriate planes shown in the figure, i.e. in the tool, on the contact zone and in the chip. All curves show a similar magnitude around 550 °C and a concave shape, which is not in line with theoretical assumed temperature distributions along the rake face [4]. However, the disturbance in the infrared image is considerably high. The orthogonal horizon plot shows the temperature curve through the contact zone at three different, arbitrarily chosen planes. For the two planes in chip direction, a clear maximum value can be identified. The slope of the curve on both sides of this local maximum is corresponding to the heat partition ratio in chip and tool. An analysis of the ratio reveals that around 10% of the heat flows into the chip (assuming a heat conductivity of λ_{chip} = 45 W/mK for the chip and λ_{tool} = 88 W/mK for the tool).

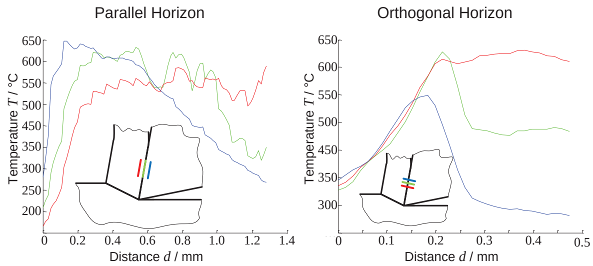

Fig. 3. Parallel and Orthogonal Horizon Plot at the Rake Face [5]

The computation is only a rough value, however corresponds to conclusions from other authors for cutting with considerable cutting edge radius and decreased chip thickness [6].

In Fig. 4 the investigation of the shear zone is presented. The temperature slopes in the work piece, on the shear zone and in the chip show a similar behavior for all planes. For the shear zone, the temperature distribution is characterized more by a convex behavior.

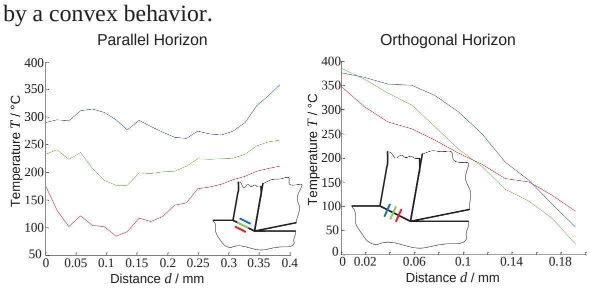

Fig. 4. Parallel and Orthogonal Horizon Plot at the Shear Zone [5]

The temperature at the shear zone was found around 250 °C. Regarding the orthogonal horizon plot, a clear distinction of the shear zone is not possible. The temperature appears as a steady decreasing curve without any local maximum or minimum value. This fact shows that for the regarded broaching process, the shear zone should be interpreted rather as a bulk heat source than a thin ideal zone.

3. Numerical Investigation

If the heat sources in a cutting process are known, the use of heat fluxes as boundary conditions is advantageous, since no temperature measurements are required for predicting the temperatures of the cutting tool. However, these heat sources are usually calculated through usage of parameters for friction, the output power of the machine, or the cutting force and