Experimental Identification of Convective Heat Transfer in Machine Tools

P. Kohút, O. Horejš, M. Mareš

Abstract—**The accuracy of machining is strongly influenced by the thermal deformation state of the machine tool structure. Thus it is very important, in machine tool design, to have a good knowledge of the relation between temperature field and deformation. Consequently, it is important to know the relations among the ways of heat transfer through the structure. In the past, convective heat transfer was rather neglected compared to conductive heat transfer. With increasing accuracy the convective part of heat transfer needs to be taken into account. The phenomenon of convective heat transfer between a solid part and an ambient fluid is described by the heat transfer coefficient (HTC). Due to its complexity, this physical quantity needs to be evaluated experimentally, especially under the conditions of machine tool applications. The experimental approach is important in providing valuable data for the improvement of computational models.**

The paper describes a technique that is being developed for direct evaluation of HTC in machine tool applications. The method is based on a balance of thermal fluxes through a probe itself. Calibration of the probe is necessary. The experiments and tests performed on the latest probe design are described and previous measurements and results are discussed.

Index Terms—**convection, experiment, heat transfer coefficient, identification.**

I. INTRODUCTION

THERMAL effects on machine tools cause up to 70% of machining inaccuracy [1]. In spite of the statement that "reliable physical modeling of thermo-elastic machine deformations is impossible because of the described complex interrelations and the unknown boundary conditions" [2], modeling of thermal deformation is a very important instrument for increasing the accuracy of the machining process, and many researchers are currently developing techniques to identify the interrelations and other conditions.

Thermal simulation tools are used – not only in the machine tool design stage – to significantly reduce the number of experiments and prototypes and, consequently, the costs. As mentioned above, the main problem of the simulation approach is that it requires the implementation of well-established boundary conditions.

Interaction between the machine tool structure and the surrounding air is usually modeled with convective and radiation heat transfer mechanisms. Whereas heat dissipation by radiation can be modeled using known emissivity, the complexity of convective heat transfer, characterized by Newton's cooling law, lies in the value of the heat transfer coefficient (HTC). Many studies have been devoted to the investigation of natural as well as forced convection, and a number of correlation equations are available in the literature, e.g. [3], [4]. Due to the complexity of machine tool geometry and low predictability of conditions during the machining process, the correlations can only be adopted to a limited extent. It is therefore necessary to develop techniques for experimental evaluation of HTC.

Several attempts have been made to evaluate the heat transfer coefficient experimentally. E.g. in [5] the HTC sensor contained a heat source, insulated from the structure to which the probe was fixed. *Jedrzejewski et al* have developed a method for evaluating HTC, based on measuring the temperature of a heated probe and identifying the linear part of the temporal relationship which localizes a thermally stable state. The relation can be expressed as

$$HTC = f\left(\frac{\ln \Delta T_1 - \ln \Delta T_2}{t_2 - t_1}\right), \tag{1}$$

where T denotes temperature and t stands for time. The authors use the method under conditions of convective heat transfer forced by the moving parts of the machine structure.

In former works [6], [7] we developed a measurement procedure for HTC identification in open moving air, using a probe in the form of a heated flat plate located in a channel. The calibration of the sensor is based on the fitting measured probe temperature response in a transient state with a suitably shaped exponential-type function.

In this work we present a completely new sensor, developed with respect to *in situ* conditions of measuring the wall heat transfer coefficient in machine tools. The sensor is tested under forced flow conditions at temperatures up to approx. 100 °C. The sensor is now considered to be operational also under natural and mixed convection conditions.

II. CONVECTIVE HEAT TRANSFER

Convective heat transfer is caused by moving fluid. With forced convection fluid motion is induced by an external

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source of pressure difference (e.g. fan, propeller, wind). With natural, or free, convection it is induced by an unstable thermal field resulting in changes of fluid density, and consequent buoyancy forces imposed on the fluid. Convective heat transfer is usually calculated as follows:

$$Q_{conv} = h(T_W - T_\infty)A\,, \tag{2}$$

where h stands for HTC, Q_{conv} for convective heat flux, T_{W} for wall temperature and T_∞ for ambient temperature, and A is the area. The number of variables that HTC depends on is reduced by using dimensionless parameters. Among these parameters are the Nusselt number *Nu*, the Grashof number *Gr*, the Reynolds number *Re* and the Prandtl number *Pr*.

For free or natural convection HTC is calculated from a criteria equation usually in the form

$$Nu = hL_{char} / \lambda = f(Gr, \mathrm{Pr}) = C(Gr\,\mathrm{Pr})^{m} \tag{3}$$

whereas under forced convection conditions HTC has to be evaluated from

$$Nu = hL_{char} / \lambda = f(\mathrm{Re}, \mathrm{Pr}) = C\,\mathrm{Re}^{m_1}\,\mathrm{Pr}^{m_2}\,, \tag{4}$$

where L_{char} denotes characteristic length, λ is thermal conductivity, C, m, m_1 and m_2 are constants that can be found in literature. The above equations are only valid for a certain range of dimensionless parameters as well as boundary conditions and other assumptions.

From the above it is clear that the influence of temperature under forced convection conditions can be neglected if the surface temperatures are close to the ambient air temperature.

The influence of irradiative heat transfer can be estimated using measured temperatures and known emissivity.

III. METHOD

Our approach uses the presumption of local heat flux balance. The balance of the heat fluxes in the HTC probe, together with several measured temperatures, allows for evaluating the heat transfer coefficient. HTC can be expressed in the form:

$$\sum Q_i = 0$$

$$HTC = f\left(Q_{in}, Q_{cond}, geomety\,, K, T_W, T_\infty\right), \tag{5}$$

where Q_{in} denotes the generated heat flux and K stands for the calibration function. A more detailed description, together with the calibration technique for the previous version of the HTC probe, can be found in [6].

The latest version of the HTC probe, presented here, is calibrated using velocity measurements and the known relation between velocity and heat transfer coefficient or, more exactly, between the Reynolds, Prandtl, and Nusselt numbers given by literature, with an assumption of local influence of the probe on the character of the flow and, consequently, on the convective heat transfer rate. Influence of the radiation heat transfer is also estimated as mentioned above.

IV. EXPERIMENTAL SETUP

A wind tunnel with an open test section and a rectangular nozzle (dimensions: 750 mm and 550 mm) was used to perform the testing and comparative measurements. The tunnel has been used for all current and past studies of basic characteristics and behavior of all modifications of the HTC probe. The HTC probe was fixed to the surface of a horizontally aligned thin flat rectangular plate with an aerodynamically shaped edge and rounded corners (plate dimensions: 300 mm span-vise and 400 mm stream-vise). A schematic view of the experimental setup can be seen in Figure 1. The quantities measured included oncoming velocity, input power, heat fluxes and temperatures of the probe, ambient and quiescent air. The surface and ambient temperatures were measured using a standard resistant temperature detector (RTD) Pt100 in a four-wire configuration, the oncoming velocity was measured with a rotating vane anemometer Ahlborn FV A915 S220.

The set of six HTC probes of the same construction was tested under forced convection conditions in a number of configurations: the stream-vise position of the probes varied in the range of (100 – 200) mm from the leading edge, the input power of the probe varied in the range of (0.3–2.5) W and the maximum oncoming velocity was 16 m/s. The surface temperature of the HTC probe ranged from 20 °C to 95 °C. The uncertainty of the temperature and velocity measurements was up to 0.3 °C and 0.2 m/s respectively.

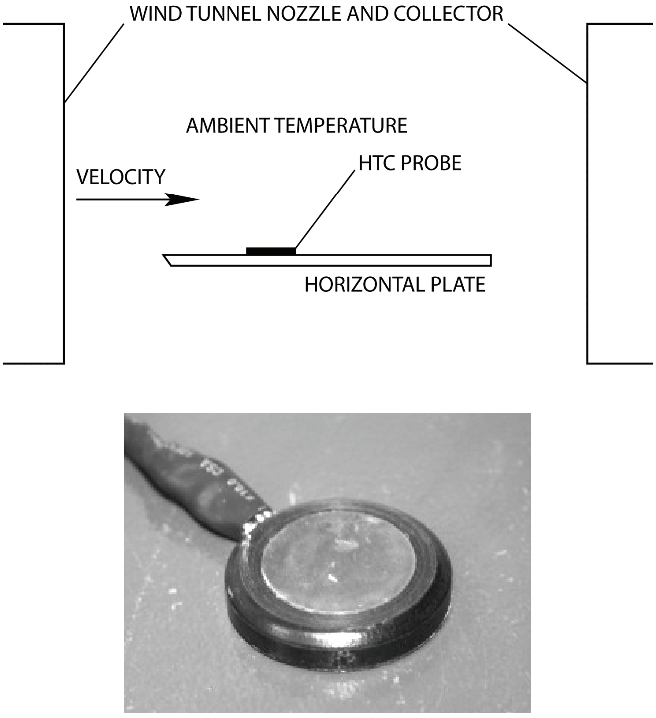

Fig. 1. A schematic view of the experimental setup and the probe.

Flow visualization using glycerin smoke generated by a heated wire was used to study the qualitative character of the boundary layer behavior in the vicinity of the probe fixed to the plate.

V. RESULTS AND DISCUSSION

A. *Early version*

The very first HTC probe consists of a thin metal plate (dimensions 100 mm x 100 mm) equipped with a defined heat source and several RTD sensors. Constant heat flux model was used in calibration procedure due to dimensions and construction of the probe. This type was successfully tested and calibrated to measure HTC in open air flow parallel to the plane defined by the plate. An example of measured and evaluated data is in Figure 2, where Nu_Q stands for Nusselt number under constant heat flux conditions. For more details about this measurement see references [6], [7].

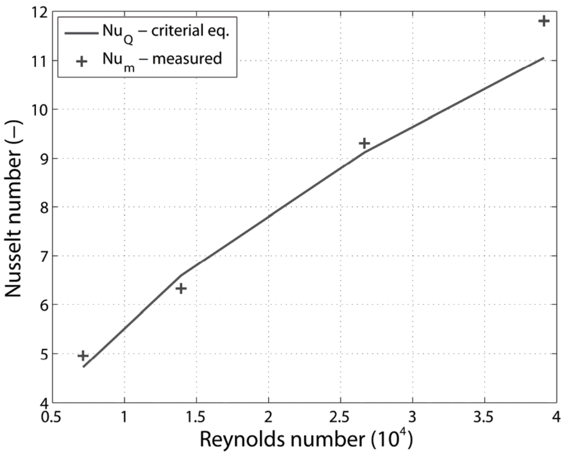

Fig. 2. Values of Nusselt number as a function of the Reynolds number [3].

In order to obtain information about the heat transfer coefficient on the wall for a better description of the boundary conditions, the measurement technique and evaluation method were modified as well as the probe itself. The probe consisted of a defined heat source equipped with a commercial heat flux meter and two RTD temperature sensors. This probe construction was tested and used to measure HTC on the wall.

Due to the construction of the probe, most of the generated heat was lost via conduction into the wall the probe was attached to. This led to a poor convection-conduction ratio of approximately 10%. This, together with the declared relative uncertainty of the heat flux evaluation, via a commercial sensor, which was 6%, had a negative impact on the accuracy of this version of the probe.

B. *Modified probe*

In order to obtain a better convection-conduction ratio in the heat flux balance, as well as for other reasons, several modifications were introduced into the design of the probe, leading to the creation of an almost completely new probe.

The latest probe with a more robust construction consists of a defined heat source and three RTD elements. Modified construction together with presumption of the constant temperature of the plate allowed us to use constant temperature model for calibration of the probe. The character of the behavior of this probe confirmed its ability to detect changes in flow and, consequently, in convection heat transfer. However, calibration is inevitable because of the more complicated geometry and construction of the probe. Figure 3 shows an example of data calibrated for constant temperature condition compared to the values of HTC from a criterion equation in the form (e.g. [3])

$$Nu_x = C\,\mathrm{Re}_x^{m_1}\,\mathrm{Pr}^{m_2} = 0.664\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{0.33}, \qquad (6)$$

where stream-vise dimension of the plate was used as a characteristic length L_{char}. The sensor reaches a stable state approximately 100-300 seconds after a change in flow regime (figure 3). Figure 4 shows that the calibrated measured HTC values in the form of nondimensional Nusselt number $Nu_{(1\text{-}3)}$ are in very good agreement with the semi-empirical Nu_T values.

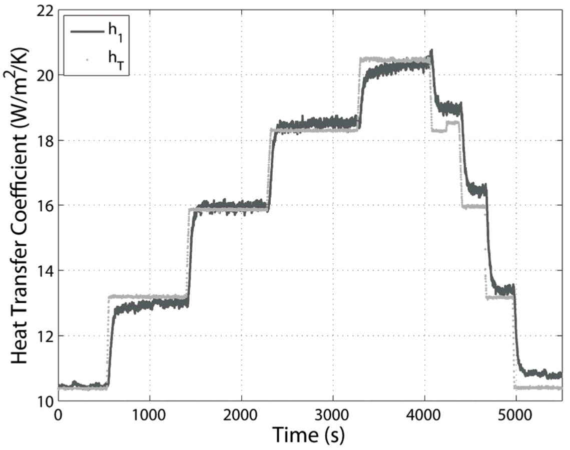

Fig. 3. Latest probe calibration - HTC h_T from criteria eq. [4] compared to measured h_1- as a function of time.

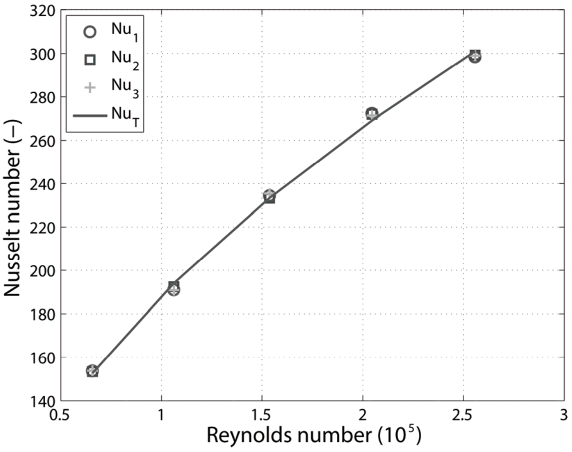

Fig. 4. Latest probe calibration – Nusselt number Nu_T from criteria eq. [4] compared to measured values $\mathrm{Nu}_{1,2,3}$ - related to Reynolds number.

Visualization experiments have confirmed that the flow in the vicinity of the plate is influenced by the probe only in a region of 2-3 diameters of the probe in the span-wise direction. Only a small separation region was observed in the flow behind the probe, with fast reattachment to the plate.

It needs to be said that the visualization technique used only produced reliable data for oncoming velocity values up to 5 m/s. Thus a more detailed investigation of the flow character at higher oncoming velocities is needed, even if the magnitude of the air velocities induced in machine tool applications is generally not much higher (except near high-speed cutters etc.). The influence of irradiative heat transfer is less than 2%.

VI. CONCLUSION

Compared to the previous modifications of the HTC probe [6], [7], the latest one has a significantly better heat transfer ratio, and the estimation of relative uncertainty, compared to the model used for calibration, is approximately (1-3)% of the tested range. A more robust construction with better aerodynamic properties makes it possible to use the probe under real machining conditions; on the other hand, it is probably the reason for slower reaction to fast dynamic changes. Changes in the probe design have also led to a 75% cost reduction.

The proposed calibration technique, the results of which are shown in Figure 3, will be verified in additional wind tunnel experiments and real machine tool testing.

The sensitivity of the HTC probe is currently being tested under natural convection conditions.

The aim of the research is to develop an experimental technique capable of evaluating the convective heat transfer coefficient under both forced and natural convection conditions, and to obtain better data that could be used in defining reliable boundary conditions in FEM simulations of machine tool thermal behavior.

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