A novel approach to generate non-isotropic surfaces for numerical quantification of thermal contact conductance

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Abstract. The quantification of heat flow between machine tool components is of major importance for a precise thermal prediction of the entire system. A common coupling condition between individual components is the contact heat transfer coefficient connecting the temperature field with the corresponding heat transfer at the investigated interface. However, the majority of numerical and analytical approaches assume isotropic contact surface profiles and neglect distinct surface structures caused by the manufacturing process. This assumption causes inaccuracies in the modeling as isotropic surfaces lead to an overprediction in heat transfer. Hence, this paper presents a novel approach to generate surface structures for numerical calculations considering the used machining parameters. Predicted contact heat transfer coefficients of the old as well as the new generation approach are presented and compared to experimental results offering the basis for future comprehensive investigations considering multiple parameters and materials.

1. Introduction

The modeling of thermo-mechanical interaction in machine systems is a powerful tool to increase product quality and manufacturing accuracy up to a few micron- or even hundreds of nanometers [1, 2]. In order to model the entire machine system, the thermal interaction between individual sub-systems needs to be considered. This is commonly achieved by applying the thermal contact conductance $h_c$ as a boundary condition, which relates the heat flow $q''$ and corresponding temperature drop $\Delta T$ due to the microscopic surface roughness at the contact interface. Though this phenomena has already been analytically analyzed in the 1960s and 1970s ([3, 4]), the increasing computational power enabled several numerical approaches in the last years, showing good agreement between experimental and numerical data. However, analytical as well as numerical approaches commonly assume an isotropic Gaussian height distribution of the surface profile investigated. Frekers et al. [6] already outlined that this simplification leads to overprediction of the heat transfer coefficient, as orientation and macroscopic structures due to the manufacturing process are not considered in the modeling. Helmig et al. [7] have shown experimentally that already a different orientation of surfaces manufactured with the same parameters reveal significant variations in contact heat transfer. Of course, three-dimensional surface segments can be measured to obtain the necessary height distribution for simulations, however this method requires hardly affordable high-end measurement technologies and the
move-ability and optical accessibility of the investigated components. Therefore, the aim of this work is to develop, present and evaluate a novel approach for the generation of non-isotropic surface structures featured in milling processes.

2. Numerical Approach

The utilized numerical approach can be divided into three consecutively executed sub-models: Surface Generation, Mechanical Modeling and Thermal Modeling, which are outlined in detail in work presented by Frekers et al. and Vu et al. [6, 8]. However, this section will focus on the explanation of the surface generation and gives only a short overview concerning mechanical and thermal modeling. The reader is therefore encouraged to study the previously mentioned work for a comprehensive description of the mechanical and thermal sub-model. Considering surface geometry, the approach uses a half-space modeling, meaning that each coordinate pair represents an individual surface height $z = f(x, y)$. For this investigation the same number of elements for both directions is chosen. The current modeling assumes further a Gaussian and isotropic distribution of the surface roughness based on the following probability density and autocorrelation function:

$$f(z(x, y)) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right); \quad \text{ACF}(x, y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{x^2}{\tau_x^2} - \frac{y^2}{\tau_y^2}\right)$$  \hspace{1cm} (1)

Here, $\tau_x$ and $\tau_y$ are the correlation lengths in $x$-, and $y$-direction, respectively and indicate how strong the height of neighboring surface points correlate. While a high correlation length causes a wider range of surface heights, smaller values lead to a more compact distribution of surface asperities. Further, the assumption of an isotropic height distribution leads to equal correlation length $\tau_x = \tau_y$. By using the auto correlation function a Gaussian filter $F(x, y)$ is defined, which is then used to generate the surface profile $z(x, y)$:

$$F(x, y) = \frac{2}{\tau\sqrt{\pi}} \exp\left(-\frac{2x^2 + y^2}{\tau^2}\right) \to z(x, y) = \int \int_{-\infty}^{\infty} F(x - x', y - y') z_{\text{rand}}(x', y') dx' dy'$$  \hspace{1cm} (2)

Hereby, $z_{\text{rand}}$ is a $N \times N$ matrix containing randomly distributed Gaussian numbers with standard deviation $\sigma$. Following, Figure 1a) shows a generated surface profile from the current approach with an isotropic surface height distribution. However, surfaces in contact often reveal typical textures caused by the used manufacturing process. In particular, milling processes lead to surface textures with distinct wavelengths having an significant impact on the number and distribution of contact spots. To account for these characteristics, the current surface generation procedure is extended by a super positioning principle, summing waviness and an isotropic Gaussian surface height distribution:

$$z(x, y) = \int \int_{-\infty}^{\infty} F(x - x', y - y') z_{\text{rand}}(x', y') dx' dy' + \sum_{i=1}^{n} A_i \cos\left(\frac{2\pi}{\lambda_i} \sqrt{x'^2 + (y' - r)^2 + \varphi_i}\right)$$  \hspace{1cm} (3)

The sum operator offers the superpositioning of various wavelengths $\lambda_i$, amplitudes $A_i$ as well as phase shifts $\varphi_i$, considering further the tool radius $r$ for curvature crosswise to the cutting direction.

To validate the new method, several specimens with varying cutting parameters have been manufactured and surface line profiles are taken with a tactile line profilometer. Subsequently, a Fast Fourier Transformation of the profiles reveals a proportional relation between the cutting speed and the first two occurring dominating wavelengths of the profile. Further, the surface
Figure 1. Generated surface profiles a) Considering solely Gaussian distribution of the surface asperities and b) a superposition of waviness and isotropic distributed asperities. Subimage c) shows a qualitative cross section of the mesh grid and applied boundary conditions used in the thermal sub-model.

parameter $R_z$, the maximum distance between peak to valley, is taken as the amplitude of the wave function.

After generating the surface geometry, the mechanical deformation of the contacting interfaces is calculated, by applying the elasto-plastic half space theory [6]. As already mentioned, the reader is referred to the publications mentioned for a detailed description.

In the last step, the deformed half-space model is extended to a three-dimensional body, applying further the steady state three-dimensional temperature equation to obtain the temperature distribution inside the contacting bodies.

$$k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = 0 \quad (4)$$

For solving this equation, the finite volume approach is chosen, using a second order discretization scheme for spatial terms. Considering boundary conditions, constant temperatures are applied at the top and bottom of the domain. Non-contacting internal interfaces are set as an adiabatic boundary condition (Fig. 1c). The numerically obtained temperature field is then used to determine the transported heat flow and temperature drop across the interface and to finally calculate the contact heat transfer coefficient $h_c$.

3. Results
Following numerical results of the current as well as the new approach are presented and evaluated with experimental results obtained from the setup presented in the work by Burghold et al. [5].

Figures 2a) - c) show the results for three different contacting pairs, with increasing roughness and main wave length. In general the new surface generation approach leads to a decrease in contact heat transfer coefficient and following to a better agreement with experimental data. This decrease is in particular visible at higher loads (38 and 48 MPa) and for surfaces with comparable low (Fig 2a) and medium roughness (Fig 2b). However, for the roughest surface investigated (Figure 2c), the new approach shows only minor improvement, as the results from existing approach show already good agreement. This observation can be explained with the distribution of contact spots. As for rougher surfaces in general only few contact spots exist, their spatial distribution does only have a minor impact on the heat constriction and contact resistance. In contrast for surfaces with smaller roughness, the number of contact spots generally
increases. Whether the contact spots are clustered in a certain area, or if these are distributed homogeneously across the interface (isotropic) has a much higher impact. As this phenomena is captured with the new surface generation approach, a general improvement of results can be observed.

Figure 2. Numerically estimated contact heat transfer coefficient by isotropic and superposition surface approach for various wavelengths and roughness. The numerical data have been evaluated with experimental results. All plots share the same legend.

4. Conclusion
This paper presents a novel approach to generate non-isotropic surface profiles for the numerical estimation of contact heat transfer coefficients. The approach uses wavelength and amplitudes of measured 1-d surface profiles as input for the generation process and shows in general a better agreement with experimental data. However, particularly surfaces with small roughness show the most significant improvement, as the spatial distribution of contact spots has a major impact on the resulting contact heat transfer in this roughness regime. Future work will focus on the generation of comprehensive experimental data used for validation and enhancement of the method presented.

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