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State of the art and optimization of the energy flow in cooling systems of motorized high-speed spindles in machine tools

Juliane Weber[a,*], Linart Shabi[a], Jürgen Weber[a]

[a]*Institute of Fluid Power, TU Dresden, Helmholtzstraße 7a, 01069 Dresden, Germany*

* Corresponding author. Tel.: +49-351-463-33320; fax: +49-351-463-32136. E-mail address: juliane.weber@tu-dresden.de

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Abstract

In high-speed cutting thermo-elastic deformations of machine tool structures and motor spindles are main causes for manufacturing inaccuracies because they lead to a TCP displacement. Therefore, cooling systems are essential for controlling thermo-elastic properties.

The paper describes different cooling system designs of motor spindles. Their thermal energy flow is analyzed by CFD simulation, and measures improving the heat rejection are discussed. For future work, such models will be integrated into a virtual machine tool that enables the estimation/control of the machines' thermal behavior.

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Keywords: Machine tool; Cooling system design; Motor spindle; CFD simulation; Heat transfer; Energy flow; Roughness.

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1. Introduction

In production technology, the demands on productivity, accuracy and power efficiency have grown steadily in recent years. Especially in high-speed cutting (HSC) thermo-elastic deformations of the machine tool structure lead to a TCP-displacement and therefore, to dimensional and form errors of the workpiece. Accordingly, they have a negative influence on manufacturing quality and productivity. To counteract this problem, entire production areas were increasingly air-conditioned or long warming-up phases were included before starting the manufacturing process – only to guarantee homogeneous boundary conditions. However, such conventional measures inevitably lead to increased energy requirements. Therefore, within the Collaborative Research Center CRC/TR 96 the investigations focus on thermally unsteady boundary conditions, where correction and compensation measures influencing thermo-elastic properties of machine tools are developed, which ensure high manufacturing accuracy without an additional energy demand [6]. In this respect, fluid cooling systems of machine tools play a central role. With the optimization of their design and operation mode the heat fluxes within the machine structure can be controlled more efficiently in order to reduce thermo-elastic deformations and the necessary energy demand.

Nomenclature

c_p	Specific heat capacity (J·kg^{-1}·K^{-1})
d_h	Hydraulic diameter (mm)
D / D_W	Mean curvature / mean diameter (mm)
K	Sand-grain roughness (µm)
l	Flow length (m)
Nu	Nusselt number (-)
P/ $\dot{Q}$	Electrical power (kW) / heat flux (kW)
p	Pressure (bar)
Pr	Prandtl number (-)
Re	Reynolds number (-)
R_z	Peak-to-valley roughness (µm)
T, ϑ	Temperature (K, °C)
v	Flow velocity (m·s^{-1})
$\dot{V}$	Volume flow rate (l·min^{-1})
α	Heat transfer coefficient HTC (W·m^{-2}·K^{-1})
$\zeta_{(W)}$	Darcy friction factor for straight (coiled) pipe (-)
η	Dynamic viscosity (mPa·s)

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λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)

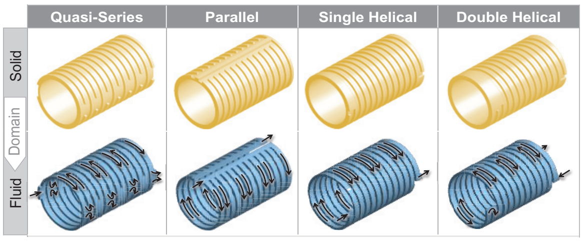

Fig. 1. Typical designs of stator cooling sleeves and resulting flow paths in the fluid domain.

2. State of the art

Previous studies focused on experimental investigation of entire fluid cooling systems in modern machine tools [12, 13]. Here, and in accordance with [2], it was found, that the motor spindle produces the largest heat amount because of losses in

- the built-in motor due to copper, iron and stray losses,
- the bearings depending on speed, preload and lubrication
- and the rotating elements due to viscosity shear of air.

Since the precision of machine tools considerably depends on the relative motion between tool and workpiece, TCP displacements resulting from thermal deformations in the main spindle have to be avoided primarily. Therefore, an effective cooling of the motor spindle with its heat losses is indispensable.

In [14, 15] the entire fluid systems and the basic structure of a motor spindle with its main heat sources was already introduced. Beside the hydraulic and the inner coolant supply system for tool and process cooling, the cooling system is used for cooling the stator and the bearings. The cooling system itself is realized by a cooling liquid that directly flows through the spindle shaft or a cooling sleeve [10]. To realize a good heat transfer between the solid bodies, the stator is press-fitted into the cooling sleeve, which consists of a thermally conductive material. In addition, the sleeve may have ribs on its outer radius improving the heat transfer into the fluid. Due to rib structures, the design of the flow channels can vary significantly, fig. 1 shows the most common ones. A similar overview is already introduced by Gebert in [5], where beside non-ripped outer contours helical and parallel channel structures are mentioned. Nevertheless, the focus of his work is on the enhancement of the spindle bearings' life cycle in order to reduce the TCP displacement. Further works deal with the analysis and improvement of the performance of motor spindles [3, 9]. Here, different spindle designs are introduced, but the focus is on the investigation of the spindle bearings; their design, lubrication, preload and resulting heat losses. In [4] Chien and Jang analyze the heat transfer in double helical cooling channels. They carry out a comparison between experimental data and numerical simulations to determine the temperature distribution in the fluid flow. Also in [7] helical channel structures are examined in detail. The focus of this work is the cooling efficiency depending on the adjustment of the channel slope and width. A detailed analysis of the fluid flow and heat transfer in helical tubes with different curvature ratios is performed in [18]. From this analysis, it is found that centrifugal forces due to channel curvature enhance the pressure drop and heat transfer in comparison with straight channels. Furthermore, Krishna experimentally investigates single helical channels with different helix angles in order to calculate the friction factor and to predict the pressure drop depending on the flow characteristic (laminar / turbulent) [8]. The influence on the heat transfer is not discussed.

In addition to literature research, existing motor spindles were analyzed, especially considering the design of their cooling systems. Therefore, existing spindles at the Institute of Fluid Power and further co-operating institutes within the CRC/TR 96 (Chair of Machine Tools Development and Adaptive Controls at Dresden University of Technology and Laboratory for Machine Tools and Production Engineering of RWTH Aachen University) were investigated. This turned out that a meandering fluid flow according the quasi-series design of the cooling sleeve (see fig. 1) is another common principle in current motor spindle designs.

This paper is focusing on the comparison between the most common cooling sleeve designs; single and double helical channel structure as well as quasi-series structure. Therefore, a 3D numerical CFD analysis is carried out for all designs. Furthermore, possibilities for the enhancement of the heat transfer between solid and fluid are analyzed.

3. Modelling setup

3.1. General setup

The general CFD workflow was described in [14]. Three major phases can be identified: preprocessing, solution and post processing. Within preprocessing particular attention is paid to the meshing quality. A grid independency study is performed for the single and double helical channel structure [14, 15]. Here it is shown that the fluid domain should have minimum eight inflation layers with a first layer thickness of 10 µm. Furthermore, the solid bodies have to be considered within simulation model due to effects of heat conduction (conjugate heat transfer CHT). In addition, a study on the parallel performance with different numbers of processors is carried out in order to save additional computation time [15]. This is of special importance executing variation studies e. g. in order to optimize geometry parameters.

Another step within preprocessing is the definition of boundary conditions, explained in detail in chapter 3.2. Before starting the solution process, the solver and physics are defined according the problem definition. As already discussed in [14, 15] the shear stress transport formulation (SST model) is used. For temperature prediction within the fluid, the heat transfer is taken into account by the energy transport equation. Due to simplifications (see 3.2) this equation is transformed to eq. *(1)*. In addition to forced convection within the fluid, heat conduction in the solid domains is taken into account (CHT). Since the bodies are rigid, no inner energy sources exist and steady state is considered, the conjugate heat transfer can be calculated according the simplified equation *(2)*.

$$\boldsymbol{\nabla} \cdot (\rho \boldsymbol{U} e) = \boldsymbol{\nabla} \cdot (\lambda \boldsymbol{\nabla} T) + \boldsymbol{\tau} : \boldsymbol{\nabla} \boldsymbol{U} \tag{1}$$

$$0 = \boldsymbol{\nabla} \cdot (\lambda \boldsymbol{\nabla} T) \tag{2}$$