euspen's 26th International Conference &
Exhibition, Krakow, PL, June 2026
www.euspen.eu

Investigation of a novel motorised milling spindle with thermoelectric temperature control system based on a tubular Peltier module

Eckart Uhlmann[1,2], Mitchel Polte[1,2], Florian Triebel[1],
Alphin Judy[1], Roland Binninger[3], Andreas Moll[4], Jörn Sieberg[4]

[1]*Technische Universität Berlin, Institute for Machine Tools and Factory Management IWF, Pascalstr. 8-9, 10587 Berlin, Germany*
[2]*Fraunhofer Institute for Production Systems and Design Technology IPK, Pascalstr. 8-9, 10587 Berlin, Germany*
[3]*Fraunhofer Institute for Physical Measurement Techniques IPM, Georges-Köhler-Allee 301, 79110 Freiburg, Germany*
[4]*FISCHER Deutschland GmbH, Marie-Curie-Strasse 2, 40764 Langenfeld, Germany*

triebel@iwf.tu-berlin.de

Abstract
Driven by ongoing technological advancements across various industrial sectors such as optics, automotive engineering and information technology, a growing demand for the production of components with geometrical and dimensional accuracies at the submicron scale can be identified. In high-precision machining, the thermomechanical behaviour of machine tools is critical. Motorised spindles represent a significant heat source within machine tools and their thermal behaviour is essential for the achievable working accuracy. Electrical and mechanical power losses in the motor drive and bearings result in the induction of heat into the shaft and housing of the motorised spindle. Despite the implementation of advanced water-cooling systems, these heat flows result in elevated temperatures, which subsequently lead to thermally induced deformation of the components, directly resulting in a displacement of the tool centre point. With the intention to improve the thermoelastic behaviour, a novel thermoelectrically temperature controlled motorised milling spindle was developed. Within this spindle, 40 Peltier stripes are arranged circumferentially around the front bearings, thus forming a tubular Peltier module. This Peltier module enables the adjustment of heat flow between the front bearings and the water-cooling system. Based on this, a precise temperature control at the front bearings is implemented. The present study investigates a prototype of this spindle and demonstrates that the thermoelectric system is capable of controlling temperatures within the range of 30 °C ≤ ϑ ≤ 40 °C. It is shown that temperature control can be achieved with a maximum temperature deviation of $\Delta\vartheta_{max}$ = 1.1 °C under changing rotational speeds. A test procedure is proposed, which involves incrementally rising rotational speeds within the range of 10,000 1/min ≤ n ≤ 50,000 1/min, followed by a temporary spindle stop. Maintaining a constant front bearing temperature results in a 16 % decrease in the change in axial shaft displacement during this test procedure when compared to a reference spindle equipped with a conventional water-cooling system.

Control, Spindle, Temperature, Thermal error

1. Introduction

Amid the continuous evolution of advanced manufacturing technologies across industrial sectors such as optics, automotive engineering, and information technology, the demand for components with geometrical and dimensional accuracies in the submicrometer range constantly increases [1]. However, achieving and maintaining such accuracy is affected by thermally induced errors, which account for up to 75 % of the total error in precision parts [2]. Heat flows $\dot{Q}$ generated by friction and energy conversion within the machine tool lead to non-uniform thermal gradients. These variations in temperature ϑ cause thermal deformation δ_{th} of machine tool components, resulting in tool centre point-displacement d_{TCP} and therefore a reduction in machining accuracy [2]. The motorised spindle is considered to be one of the primary heat sources within machine tools [3]. The integrated motor drive induces heat flows $\dot{Q}_{ind}$ due to electrical losses in addition to bearing and fluid friction losses that occur at high rotational speeds n [4]. To achieve higher machining accuracy, the effects of the thermal loads must be reduced by means of appropriate cooling concepts. Denkena et al. [4] provide a comprehensive overview of cooling strategies for motorised spindles and distinguish between passive and active approaches. A further distinction is made based on the cooling target, differentiating between the cooling of the spindle bearings, the stator, and the shaft.

Passive cooling strategies rely on heat transfer by convection to the ambient air, typically enhanced by heat sinks. Active cooling concepts deploy a flowing cooling medium which is applied in close proximity to the heat sources [4, 5].

A variety of passive cooling concepts use heat pipes of different shapes and configurations, which are integrated inside the spindle housing or in the spindle shaft. In addition, external heat sinks are placed outside the spindle housing to enhance convective heat flow $\dot{Q}_{conv}$ [6-9]. Common approaches of active cooling using water as fluid include differently designed cooling channels [9-10].

Beyond passive and active cooling, approaches to actively control the spindle temperature ϑ_{sp} offer the possibility to maintain a constant spindle temperature ϑ_{sp} and minimize temperature fluctuations during operation. Jonath et al. [11] extend the heat pipe-based cooling concept by controlling the rotational fan speed n_F, which affects the convective heat flow $\dot{Q}_{conv}$. The additional integration of a heating foil enables the induction of a heat flow $\dot{Q}_{ind}$. Utilizing the bidirectional heat transport capability of the heat pipes, this setup enables control of the spindle temperature ϑ_{sp}. As a result, a reduction of the axial shaft displacement d_s by 62 % compared to the uncontrolled configuration is achieved.

WAKIYA ET AL. [12] focus on the cooling unit and controlling the cooling fluid temperature ϑ_{fl} based on the spindle's internal temperature ϑ_{sp}, by mixing two fluid streams at different fluid temperatures ϑ_{fl}. This enables a reduction of changes in spindle temperature ϑ_{sp} caused by changes in rotational speeds n and variations in the ambient temperature ϑ_{amb}. The results show a remaining maximum spindle temperature variation $\Delta\vartheta \leq 0.3$ °C during a change of rotational speed from n_1 = 10,000 1/min to n_2 = 15,000 1/min.

An alternative approach for realizing an active temperature control system is the utilization of Peltier modules. A Peltier module is composed of an alternating pattern of p-doped and n-doped semiconductor legs arranged between two ceramic plates, electrically connected in series and thermally in parallel. Based on the Peltier effect, first discovered by PELTIER [13], a heat flow $\dot{Q}_{pel}$ within the Peltier module can be generated by applying an electric current I_{pel}.

The applicability of this approach is demonstrated by FAN ET AL. [14]. Peltier modules are attached to the outer surface of a spindle housing. This serves to establish a thermal equilibrium between the heat flow $\dot{Q}_{gen}$ generated by the spindle and the heat flow $\dot{Q}_{abs}$ absorbed by the Peltier modules. A reduction of the axial shaft displacement d_s by 58.6 % at a rotational speed n = 10,000 1/min results [15].

UHLMANN ET AL. [16, 17, 18] developed an actively temperature-controlled motorised spindle utilising prismatic Peltier modules. Three groups of Peltier modules, each independently controllable, are integrated between the water cooler and the front and rear bearings, as well as the stator. This configuration enables precise control of the temperature ϑ_{sp} within the spindle. Using this approach, the warm-up time t_w required to reach the thermal steady state of the axial shaft displacement d_s can be reduced by up to 79 %.

With the aim of reducing the expanses of integrating a thermoelectric temperature control system within motorised spindles, the companies FISCHER DEUTSCHLAND GMBH and DR. NEUMANN PELTIER-TECHNIK GMBH, in conjunction with the research institutes FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM and the INSTITUTE FOR MACHINE TOOLS AND FACTORY MANAGEMENT IWF developed a novel thermoelectric temperature control system based on a tubular Peltier module. The integration of a tubular Peltier module between the bearings and the water cooler enables active transfer of heat Q. In comparison with the use of solely conductive elements, as in a state-of-the-art spindles, this offers the advantage that the bearing temperature ϑ_b can be controlled independently of the thermal load. Additionally, due to the bidirectional functionality of the Peltier effect, there is also the possibility of heat transfer from the cooling liquid to the bearings.

The present study investigates the characteristics of the temperature control system within a first prototype spindle, shown in figure 1. Furthermore, the influence of a constant front bearing temperature ϑ_{fb} on the axial shaft displacement d_s is examined.

2. Thermoelectrically temperature-controlled spindle

2.1. Experimental setup

The prototype motorised spindle, shown in figure 1, is based on a high-speed spindle of type MFW-840/50 HSK-E25 by FISCHER DEUTSCHLAND GMBH, Langenfeld, Germany, and equipped with the novel thermoelectric temperature control system. Previous work shows, that an active temperature control at the front bearing seat has the highest impact on the axial shaft displacement d_s. Therefor the rear bearings and the motor drive remain cooled by a conventional water-cooling system. The tubular Peltier module is composed of a number n = 40 Peltier stripes circumferentially arranged around the front bearing seat, shown in figure 2. The water cooler is shrink-fitted to the arrangement of the Peltier stripes, ensuring a mechanical and thermal connection. The assembly of the front bearing seat, the tubular Peltier module and the water cooler is shown in figure 2 b).

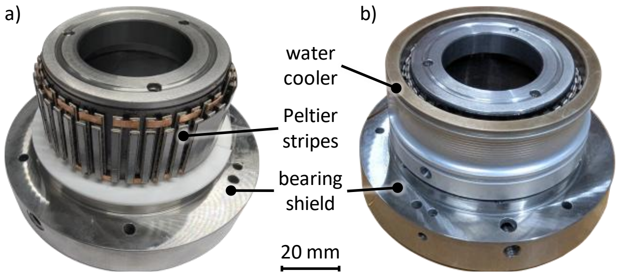

Figure 2. Assembly of the front bearing seat;
a) installed Peltier stripes; b) Peltier stripes and water cooler.

Depending on the direction of the applied Peltier current I_{pel}, the Peltier strips can transfer heat Q from the bearing shield into the water cooler or vice versa. In figure 1, the heat flows $\dot{Q}$ are illustrated in a scenario where the heat flow $\dot{Q}_{ind}$ induced by the bearings is transferred to the cooling liquid. The absorbed heat flow $\dot{Q}_{abs}$ and the emitted heat flow $\dot{Q}_{emi}$ depend on the Seebeck coefficient α, the thermal conductance C and the electrical resistance R of the Peltier strips [19].

$$\dot{Q}_{abs} = \alpha\, I_{pel}\, \vartheta_1 - C\,(\vartheta_2 - \vartheta_1) - (I_{pel}^2\, R)/2 \tag{1}$$
$$\dot{Q}_{emi} = \alpha\, I_{pel}\, \vartheta_2 - C\,(\vartheta_2 - \vartheta_1) + (I_{pel}^2\, R)/2 \tag{2}$$

The absorbed heat flow $\dot{Q}_{abs}$ is determined by the Peltier current I_{pel}, as demonstrated in equation 1. Therefore, it is feasible to control the front bearing temperature ϑ_{fb}, with the Peltier current I_{pel} serving as the controlled variable. For the purpose of measuring the front bearing temperature ϑ_{fb}, a resistance thermometer of type PT1000 by TEMPERATUR

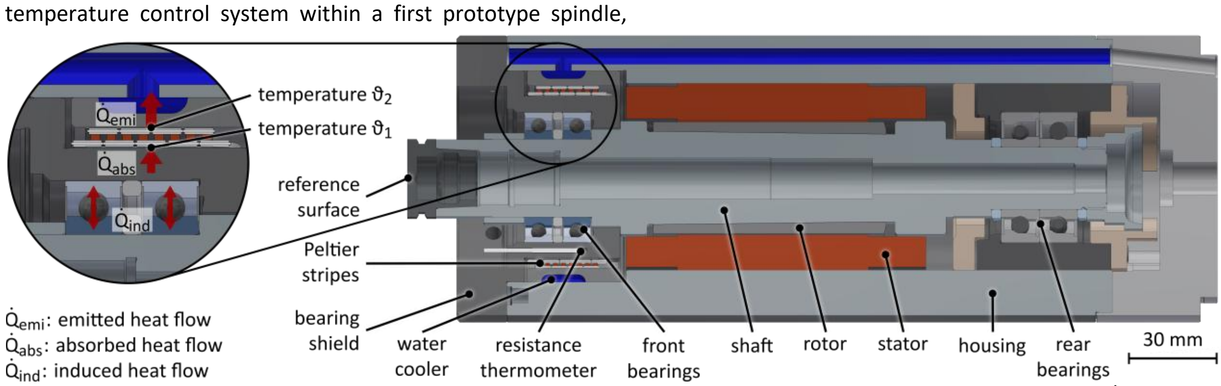

Figure 1. 3D-model of prototype motorised milling spindle with thermoelectric temperature control system. Induced heat flow $\dot{Q}_{ind}$ by the front bearings, absorbed heat flow $\dot{Q}_{abs}$ and emitted heat flow $\dot{Q}_{emi}$ by the Peltier stripes are illustrated, for the scenario of cooling the bearings.

MESSELEMENTE HETTSTEDT GMBH, Maintal, Germany, is integrated between the front bearings and the Peltier stripes.

The Peltier stripes are electrically connected in series and the Peltier current I_{pel} is controlled by a Peltier controller of type PWR-CTRL-M of DR. NEUMANN PELTIER-TECHNIK GMBH, Neuried, Germany. The Peltier controller is able to control the front bearing temperature ϑ_{fb} by means of a PID-controller, whose parameters are identified via an autotune function.

The prototype spindle is operated on a spindle test bench in a laboratory at the FISCHER DEUTSCHLAND GMBH with a maximum rotational speed n_{max} = 50,000 1/min. The spindle is water-cooled at a volumetric flow rate $\dot{V}$ = 3 l/min and a constant fluid temperature ϑ_{fl} = 20 °C with a temperature deviation of $\Delta\vartheta_{fl} \leq 0.1$ °C. The axial shaft displacement d_s of the spindle is measured at a plane reference surface of a tool holder by means of an eddy current sensor of type SGS4701 by MICRO-EPSILON MESSTECHNIK GMBH & CO. KG, Ortenburg, Germany.

2.1. Experimental procedure

In order to examine the capacity of the temperature control system for reference tracking, the front bearing temperature is set to ϑ_{fb} = 30 °C and then changed to ϑ_{fb} = 40 °C before being reset to ϑ_{fb} = 30 °C. The purpose of these tests is to examine the settling time t_s and the maximum overshoot Δh of the closed-loop system. The settling time t_s is specified as the point at which the measured data is first bounded by tolerance band of width w = 0.2 °C, and subsequently remains within these boundaries. This implies that the boundary of the tolerance band is located at ± w/2 = ± 0.1 °C around the setpoint of the front bearing temperature ϑ_{fb}.

Subsequently, the controller's capability for disturbance rejection is evaluated by means of an incremental increase in the rotational speed n. The changes in rotational speed n are accompanied by a change in the heat flow $\dot{Q}_{ind}$ induced at the bearings. The test procedure is specified in table 1. Upon attaining the maximum rotational speed n_{max} = 50,000 1/min, the spindle is brought to an immediate stop. Thereafter, following a downtime of t_d = 2,700 s, the spindle is accelerated to its maximum rotational speed n_{max}. This enables the evaluation of the deviation of the controlled front bearing temperature $\Delta\vartheta_{fb}$ from its setpoint, due to thermal disturbances. The quantification of the maximum change in axial shaft displacement Δd_s is enabled by the deceleration from maximum rotational speed n and subsequent acceleration to maximum speed n.

Table 1. Test procedure with incrementally changes in rotational speed n.

step	duration Δt	rotational speed n
1	900 s	0 1/min
2	900 s	10,000 1/min
3	900 s	20,000 1/min
4	900 s	30,000 1/min
5	900 s	40,000 1/min
6	900 s	50,000 1/min
7	2,700 s	0 1/min
8	1,900 s	50,000 1/min

3. Results

As shown in figure 3, the controlled front bearing temperature ϑ_{fb} is measured while its setpoint is altered from ϑ_{fb} = 30 °C to ϑ_{fb} = 40 °C and vice versa. The measurement is conducted at standstill and rotational speed n = 25,000 1/min. It has been found that a maximum overshoot of Δh = 2.2 °C occurs at a rotational speed n = 0 1/min after the setpoint of the front bearing temperature is altered from ϑ_{fb} = 40 °C to ϑ_{fb} = 30 °C. All setpoint changes regarding the front bearing temperature ϑ_{fb} result in a settling time between 40.4 s ≤ t_s ≤ 50.7 s.

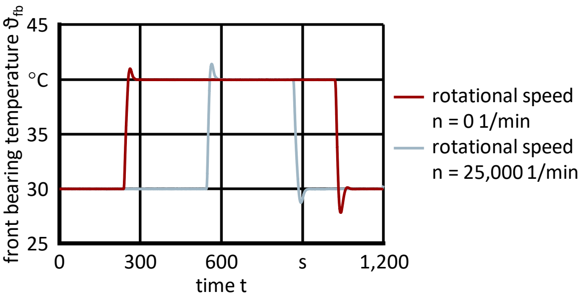

Figure 3. Setpoint alteration of front bearing temperature ϑ_{fb} at rotational speed n = 0 1/min and rotational speed n = 25,000 1/min.

Throughout the entire test procedure, specified in table 1, the setpoint of the front bearing temperature of the prototype spindle remains set to ϑ_{fb} = 30 °C. Figure 4 shows the measured front bearing temperature ϑ_{fb} during this test. It is evident that each alteration of rotational speed n leads to a deviation of the measured front bearing temperature $\Delta\vartheta_{fb}$ regarding the respective setpoint. This phenomenon persists until the measured value again reaches the setpoint. The maximum change in the front bearing temperature $\Delta\vartheta_{fb,max}$ = 1.1 °C is observed when the immediate stop is invoked, see line 6-7 in table 1. For the purpose of comparison, figure 4 shows the front bearing temperature ϑ_{fb} measured during the same test procedure with a reference spindle of type MFW840/50. It is evident that there is a positive correlation between the front bearing temperature ϑ_{fb} and the rotational speed n. When the rotational speed n is increased, the temperature rises abruptly. This is followed by a gradual rise until a steady state is reached. The maximum change in the front bearing temperature of the reference spindle during the test procedure is $\Delta\vartheta_{fb,max}$ = 10.6 °C.

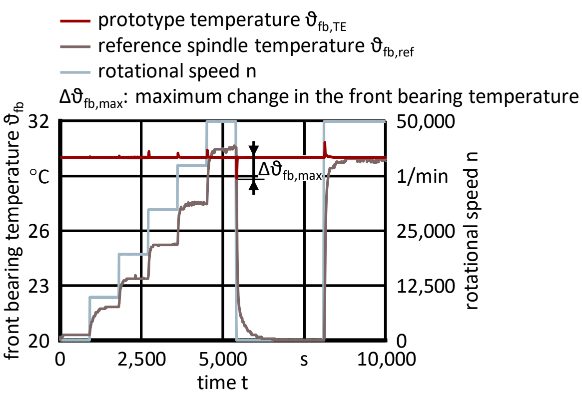

Figure 4. Measured front bearing temperature ϑ_{fb} under the influence of incrementally changing rotational speed n.

Simultaneously, the axial shaft displacement d_s is measured, see figure 5. It is evident that the axial shaft displacement d_s increases with the incremental increase in rotational speed n. The axial shaft displacement d_s initially rises abruptly, evolving into a slower change until a steady state is reached. The abrupt rise in axial shaft displacement d_s can be attributed to the centrifugal forces F_c acting within the angular contact ball bearings and the gyroscopic moment M_g, e.g., described by JEDRZEJEWSKI AND KWASNY [20]. The slower changes in axial shaft displacement d_s can be attributed to the thermal behaviour.

The same test procedure is performed under identical conditions with a reference spindle, see figure 5. The reference spindle is equipped with a conventional water-cooling system and differs from the prototype only in terms of the unmodified front bearing section. The measurements demonstrate a qualitatively comparable trend, whilst it can be observed that the reference spindle shows a larger change in axial shaft displacement Δd_s subject to the varied rotational speed n. For both spindles, the maximum change in axial shaft displacement Δd_s occurs at the point of change between maximum rotational speed n_{max} and spindle stop. For the reference spindle, the maximum change in axial shaft displacement is Δd_s = 33.7 µm, and for the prototype, the maximum change in axial shaft displacement is Δd_s = 28.2 µm. This is equivalent to a 16 % reduction.

A further quantitative difference in the measurements, shown in figure 5, can be observed after the spindle stop. In this instance, the axial shaft displacement d_s of the prototype exhibits a significantly slower decrease in comparison to that of the reference spindle. This can be attributed to the maintenance of the setpoint of the front bearing temperature at ϑ_{fb} = 30 °C, even at standstill. This results in a reduction of the cooling rate of the affected spindle components.

Controlling the front bearing temperature ϑ_{fb} independently of the thermal load enables the spindle components to be prevented from cooling down during downtime t_d due to a tool or workpiece change. This has the potential of reducing the time to reach a steady state with regard to the axial shaft displacement d_s, i.e. the warm- up time t_w after a downtime t_d.

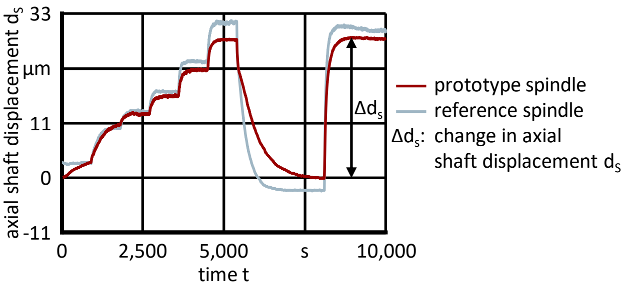

Figure 5. Measured axial shaft displacement d_s of prototype and reference spindle during the test procedure specified in table 1.

4. Conclusion and future work

The present work introduces a novel thermoelectric temperature control system for motorised spindles, based on a tubular Peltier module. A prototype spindle was equipped with such system at the front bearing seat. This prototype could be demonstrated capable of controlling front bearing temperatures within the range of 30 °C ≤ ϑ_{fb} ≤ 40 °C. Furthermore, it was demonstrated that thermal disturbances caused by changes in rotational speed n lead to a maximum change in the front bearing temperature of $\Delta\vartheta_{fb,max}$ = 1.1 °C, where the maximum change in the front bearing temperature of the reference spindle is $\Delta\vartheta_{fb,max}$ = 10.6 °C. It was also demonstrated that controlling the front bearing temperature ϑ_{fb} exerts an influence on the axial shaft displacement d_s. In particular, maintaining a constant front bearing temperature of ϑ_{fb} = 30 °C results in a 16 % decrease in the change in axial shaft displacement Δd_s during changes of the rotational speed n when compared to a reference spindle. Furthermore, the measurement of the axial shaft displacement d_s indicates, that controlling the front bearing temperature ϑ_{fb} independently of the thermal load has an effect on the cooling rate of spindle components.

A future objective is to substantially minimise the warm-up time t_w following a spindle stop, for instance after a workpiece or tool change in the machine tool. As demonstrated in previous research of Uhlmann [18], this objective can be accomplished by increasing the front bearing temperature ϑ_{fb} during downtime t_d of the spindle. Reducing warm-up time t_w decreases non-productive time, contributing to increased productivity.

Acknowledgements

The authors would like to express their sincere gratitude to the Dr. Neumann Peltier-Technik GmbH for their invaluable support in conducting this research and for provision of a Peltier controller.

This work was funded within the Fraunhofer-DFG transfer program by Fraunhofer Society and Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 529738427.

References

[1] Uhlmann E, Mullany B, Biermann D, Rajurkar K P, Hausotte T and Brinksmeier E 2016 Process chains for high-precision components with micro-scale features *CIRP Ann.* **65** (2) 549-572
[2] Mayr J et al. 2012 Thermal issues in machine tools *CIRP Ann.* **61** (2) 771-791
[3] Brecher C and Wissmann A 2011 Compensation of thermo-dependent machine tool deformations due to spindle load: investigation of the optimal transfer function in consideration of rough machining *Prod. Eng. Res. Devel.* **5** (5) 565-574
[4] Denkena B, Bergmann B and Klemme H 2020 Cooling of motor spindles—a review *Int. J. Adv. Manuf. Technol.* **110** (11–12) 3273-3294
[5] Li S and Wu Y 2010 A study on oil/air lubrication and preload of a high frequency fully ceramic motor spindle *International Conference on E-Product E-Service and E-Entertainment 2010* 1-4
[6] Putra N and Ariantara B 2017 Electric motor thermal management system using L-shaped flat heat pipes *Appl. Therm. Eng.* **126** 1156-1163
[7] Fang G, Yuan W, Yan Z, Sun Y and Tang Y 2019 Thermal management integrated with three-dimensional heat pipes for air-cooled permanent magnet synchronous motor *Appl. Therm. Eng.* **152** 594-604
[8] Kajikawa S, Morita S, and Sugita N 2024 Cooling of spindle shaft for machining center using heat exchangers *J. Adv. Mech. Des. Syst. Manuf.* **18** (3) 1-15
[9] Xia C, Fu J, Lai J, Yao X and Chen Z 2015 Conjugate heat transfer in fractal tree-like channels network heat sink for high-speed motorized spindle cooling *Appl. Therm. Eng.* **90** 1032-1042
[10] Huang Y-H, Huang C-W, Chou Y-D, Ho C-C and Lee M-T 2016 An experimental and numerical study of the thermal issues of a high-speed built-in motor spindle *Smart Sci.* **4** (3) 160-166
[11] Jonath L, Luderich J, Brezina J, Gonzalez Degetau A M and Karaoglu S 2023 Improving the thermal behavior of high-speed spindles through the use of an active controlled heat pipe system *3rd International Conference on Thermal Issues in Machine Tools (ICTIMT2023) Lecture notes in production engineering* 203-218
[12] Wakiya S, Ishida R, Kusuyama J and Nakao Y 2023 Temperature control performance of a built-in motor spindle by developed temperature feedback control system *Int. J. Autom. Technol.* **17** (5) 512-520
[13] Peltier J C A 1834 Nouvelles expériences sur la caloricité des courants électrique *Ann. Chim. Phys.* **2** (56) 371-386
[14] Fan K, Xiao J, Wang R and Gao R 2022 Thermoelectric-based cooling system for high-speed motorized spindle I: design and control mechanism *Int. J. Adv. Manuf. Technol.* **121** (5-6) 3787-3800
[15] Fan K, Xu R, Wang R and Gao R 2022 Thermoelectric-based cooling system for high-speed motorized spindle II: Optimization and validation strategy *Int. J. Adv. Manuf. Technol.* **119** (9-10) 6521-6533
[16] Uhlmann E, Polte J, Salein S, Iden N, Temme P, Hartung D and Perschewski S 2020 Entwicklung einer thermoelektrisch temperierten Motorspindel *wt Werkstattstechnik online* **110** (5) 299-305
[17] Uhlmann E, Polte M, Triebel F, Salein S, Temme P, Hartung D and Perschewski S 2022 Reduction of warm-up period after machine downtime by means of a thermoelectric tempered motorized milling spindle *euspen SIG Meeting: Thermal Issues*
[18] Uhlmann E 2023 Recent advances in precision, sustainability and safety of machine tools *J. Mach. Eng.* **23** (3) 5-25
[19] Goldsmid H J 2016 *Theory of Thermoelectric Refrigeration and Generation* Springer Ser. Mater. Sci. **121**
[20] Jedrzejewski J and Kwasny W 2010 Modelling of angular contact ball bearings and axial displacements for high-speed spindles *CIRP Ann.* **59** (1) 377-382