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Indirect workpiece cooling system for micro milling based on a Peltier element

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Abstract
Micro milling is characterized by its high flexibility and the large variety of machinable materials. However, the process is limited by high abrasive wear of the cutting edge. Tool wear can be reduced by the application of metalworking fluids. The main tasks of metalworking fluids are cooling and lubrication. However, until now it is unknown how important the cooling part and the lubrication part are when micro milling with 50 µm diameter micro end mills. Since it is not possible to separate the two effects when using a metalworking fluid, it is necessary to choose an alternative approach. Thus, no metalworking fluid is to be used, but a unit that only cools. In this way it is possible to determine which influence the cooling alone has on the process results. Through the subsequent comparison to the application of metalworking fluid and to dry machining, it can be determined how important lubrication is for micro milling with micro mills with diameters of < 50 µm. In this paper, the novel cooling system for micro machining processes is described. The system was developed for the integration into a desktop-sized machine tool. The process cooling is realized as an indirect workpiece cooling through a Peltier element underneath the sample. A Peltier element is an electrothermal converter based on the Peltier effect. A current flow creates a temperature difference between the two sides of the Peltier element. The cold side is used for indirect workpiece cooling, the heat generated on the other side has to be dissipated via a heat sink. This paper presents the design, functionality and the characterization of the system and shows first results when micro milling with 50 µm diameter micro end mills.

Keywords: micro milling, cooling, desktop sized machine tool, micro cutting, Peltier element

1. Introduction

Micro milling is characterized by its high flexibility and the large variety of machinable materials [1]. However, the process is limited by high tool wear, mainly caused by size effects such as the material springback, strongly negative rake angles, and material inhomogeneities [2]. Tool wear can be reduced by the application of metalworking fluids. The main tasks of metalworking fluids are cooling and lubrication, however, it is currently unclear whether cooling or lubrication is more important for micro milling using ultra-small micro end mills (d < 100 µm). In micro milling, the influence of cooling lubrication has mostly been studied using the strategies flood cooling and minimum quantity lubrication. Since it is not possible to separate the two effects when using a metalworking fluid, it is necessary to choose strategies that allow pure process cooling to be studied. In this way it would be possible to determine which influence the cooling has on the process results. Investigations on the influence of process cooling in micro milling have rarely been carried out. One possibility for process cooling without lubrication is the use of cryogenic cooling. Examples of its use in micro milling are the application of jet cooling [3], cryogenic pre-cooling [4], or indirect workpiece cooling [5]. Another possibility of sole process cooling is the application of gaseous cooling [6–8]. The tool diameters of the micro end mills used range from 200 µm [8] to 760 µm [4], with the majority being greater than or equal to 500 µm. Most of the strategies used for process cooling are not suitable for micro milling with ultra-small micro end mills. Therefore, in this paper, a novel cooling system for micro machining processes is described.

2. Cooling system

2.1. Description

Figure 1 shows the cooling system. The indirect cooling of the workpiece (cp-titanium grade 2; 20 mm x 25 mm x 2 mm) is realized by using a Peltier element, which is located directly underneath the sample holder.

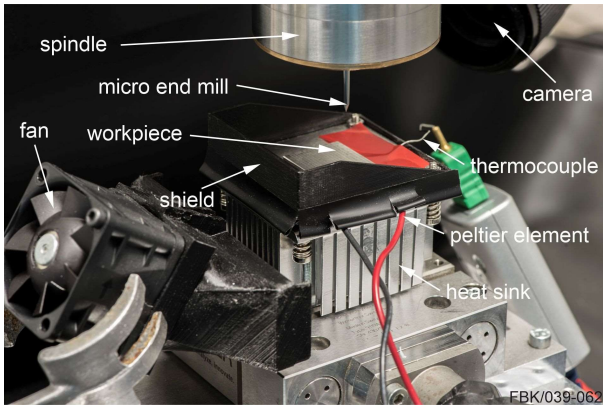

Figure 1: Experimental setup.

The Peltier element has a size of 30 mm x 30 mm x 4.7 mm with a maximum power of 18.7 W. The polarity of the Peltier element is chosen in a way that the cold side faces towards the sample. To dissipate the heat on the other side of the Peltier element, a heat sink is mounted underneath the Peltier element, which has the function of dissipating as much heat as possible. For a further increase of the cooling capacity, a fan is located at one side of the heat sink, decoupled from the machining table.

To avoid a negative influence of unwanted heating of the specimen surface by the wind flow coming from the fan, a shield was attached to the specimen holder on the fan side. The sample temperature is permanently monitored by a type K thermocouple. The heat sink is mounted on a dynamometer to record the process forces.

2.2. Characterization of the system

A characterization of the cooling system was done to determine the achievable workpiece temperatures and the influence of the ambient conditions on the system. The workpiece temperature is mainly dependent on the power applied to the Peltier element. The use of thermal paste between the heat sink and the specimen holder, the air flow of the spindle and the air flow of the fan were identified as possible factors influencing the workpiece temperature. First, the correlation between the electrical power and the sample temperature inside as well as on the surface of the sample at a spindle speed of 30,000 rpm was measured. The tests were carried out with the spindle switched on, because heat is generated by the shearing of the air in the air bearing which is blown onto the sample. Starting from a power of 0 W, the power was increased every 120 s up to the maximum achievable power of 60 W and then decreased again in the same steps. The time until the power is changed has been selected in such a way that a stable temperature can be established within this time. The temperatures were continuously recorded at two positions: on the surface of the workpiece and in an eroded hole 1 mm below the surface of the workpiece. The result of this measurement is shown in Figure 2. The following conclusions can be drawn:

- The lowest achievable temperature at the sample surface is -3 °C and -8 °C inside the sample.
- The temperature inside of the sample is always cooler than the temperature on the surface of the sample.
- The lower the temperature, the greater the temperature difference between the two measuring points (inside and outside of the sample).
- Below a temperature of 2 °C (outside), condensation forms on the sample surface and ice below -3.5 °C.
- The maximum achievable power is 60 W.

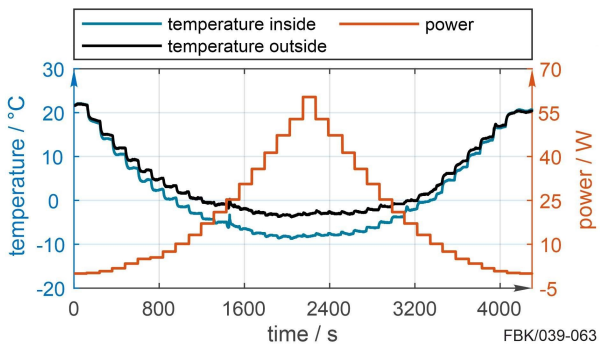

Figure 2: Correlation between the electrical power and the sample temperature inside and on the sample at a spindle speed of 30,000 rpm.

Since both condensation and ice on the sample surface hinder the performance of the investigation of pure cooling when micro milling or even make micro milling impossible for the case of ice, the range in which the sample surface stays dry was examined more closely. For this purpose, exemplarily the temperatures 10 °C and 0 °C outside of the sample, as well as the room temperature (Peltier element switched off) were selected for further measurements. Again, the temperatures on the sample surface as well as inside the sample were measured and examined more closely. Figure 3 shows the results of this measurement. The desired temperatures were achieved at powers of 3.5 W and 14 W, respectively. One aspect noticeable when comparing the temperatures inside the sample and on the sample surface is that at room temperature (0 W) temperature inside > temperature outside, at 10 °C temperature inside = temperature outside and at 0 °C temperature inside < temperature outside. This relation can be explained based on the environmental conditions, more precisely by the influence of the sealing air of the spindle. The air flow from the spindle onto the surface causes cooling of the surface at 0 W (RT). The lower the temperature generated by the Peltier element, the less this aspect is important, so that already at 0 °C the temperature of the sample inside is below that of the sample surface. However, the temperature difference between inside and outside of the sample is < 0.3 °C at 0 °C, so that for temperatures higher than 0 °C the temperatures of the sample surface and the sample inside can be considered almost the same.

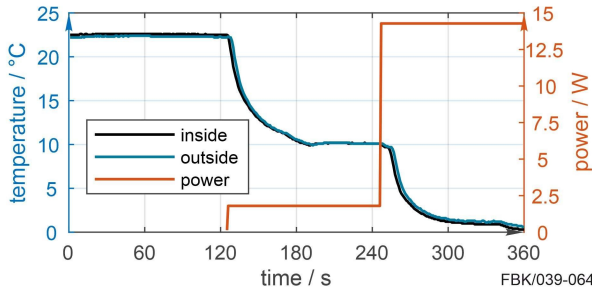

Figure 3: Difference between the external and internal sample temperature as a function of the electrical power.

In another measurement, the influence of the sealing air and additional compressed air on the sample temperature was further investigated. To show as much impact as possible, the maximum power of 60 W was chosen for the measurement. Three conditions were considered during the measurement: covered, sealing air and compressed air. In the covered condition, a sheet of paper was held between the spindle and the sample, in the sealing air condition, the spindle was above the sample at a spindle speed of 30,000 rpm and in the compressed air condition, compressed air was additionally applied to the sample as a possibility to avoid ice formation or condensation. The result is depicted in Figure 4.

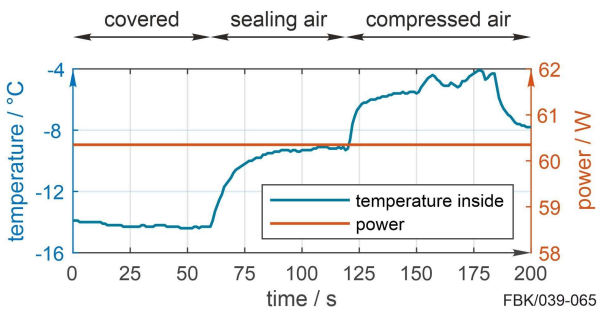

Figure 4: Influence of sealing air and additional compressed air on the sample temperature.

The lowest temperatures were reached with the covered sample. The temperature was constantly at approx. -14 °C. The temperature was increased to -9 °C by the sealing air directing onto the sample. The additional flow of compressed air against the sample resulted in a further increase in temperature. In this condition, no constant temperature could be achieved. The measured temperatures varied between -6 °C and -4 °C. In general, it can be concluded that air flows in the vicinity of the sample lead to an unwanted increase in the sample

temperature. This confirms the importance of the shield to prevent an unwanted flow of the sample through the fan. Another aspect that can be identified from this measurement is the reactivity of the system: within a few seconds after changing the condition, a constant temperature has already set in. The application of compressed air prevented ice formation or condensation on the sample to a large extent, but the fluctuating as well as increased temperature on the sample surface is not suitable for achieving stable process conditions.

Micro milling is possible in the presence of condensation, but pure workpiece cooling cannot be investigated under this condition since the condensation leads to additional cooling and lubrication by the water. Especially ice formation is very critical in micro milling: One reason for this is that the ice layer is thicker than the micro end mill length, which requires the ice to be cut as well as the workpiece material. In preliminary tests, this led to the direct breakage of the micro end mill. Another reason is the lack of the possibility to touch the surface to determine the zero point of the surface. Touching the surface before cooling the sample is not feasible, because the thermal expansion leads to a change of the zero point in the order of magnitude of the depth of cut (5 µm). Scratching after cooling the sample does not work because the surface is hidden by the ice layer.

To be able to apply lower temperatures than 0 °C, further possibilities were considered which could prevent the formation of ice on the surface. In addition to the possibility of directing compressed air onto the sample, as already shown, the application of isopropanol was investigated. In this measurement series, the surface was wetted with isopropanol and first flowed with sealing air. The sample was subsequently covered with a sheet of paper to be able to consider the influence of pure cooling without the influence of the sealing air. The result is shown in Figure 5.

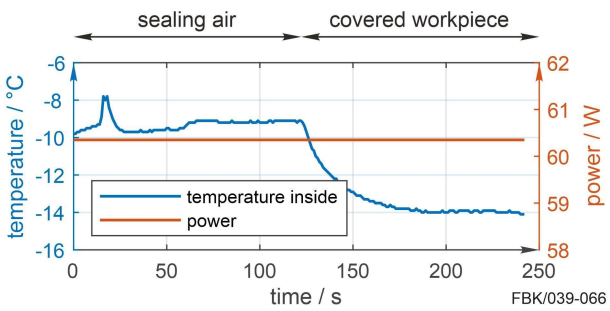

Figure 5: Use of isopropanol to prevent ice formation and its effect on sample temperature.

Similar to the result of directing compressed air onto the surface (see Figure 4), the combination of isopropanol with sealing air leads to irregular cooling of the surface. The temperatures fluctuate between -10 °C and -8 °C. These are 4 °C lower than those of the incident flow with compressed air. Covering the surface resulted in a constant temperature of -14 °C. Although the isopropanol prevents ice formation, this condition is not suitable due to the large fluctuations. In addition, the isopropanol causes additional cooling lubrication, as in the case of condensation water. The additional cooling lubrication of isopropanol or condensation is a problem for the investigation of pure cooling, but it is acceptable for cooling lubrication during micro milling. Based on the characterization, a power of the Peltier element of 14 W was selected to obtain a sample temperature of 2 °C during micro milling. In this way, the lowest possible sample temperature can be achieved without the formation of ice or condensation.

3. Experimental setup and proof of concept

3.1. Face milling

For micro milling, the cooling unit was integrated into a precision milling machine, analogous to the characterization process. Prior to micro milling, the sample was face milled at room temperature to obtain a flat surface parallel to the machining table. After face milling was completed, the cooling system was turned on. For micro milling, spindle speeds of 30,000 rpm, 120,000 rpm, and 230,000 rpm, a depth of cut of 5 µm, a feed per tooth of 1 µm and a feed travel of 1000 mm were set. Micro end mills with a diameter of 50 µm made of cemented carbide (91 % WC, 9 % Co, grain size 0.3 µm) were used. Micro milling of the first sample performed without any problems. Micro milling of the second sample resulted in breakage of several micro end mills, which raised the suspicion that distortion of the sample was evident. This was proven by touching the sample at five different locations with a new micro end mill (see figure 6) to check the distortion. A maximum difference of 17.7 µm was detected.

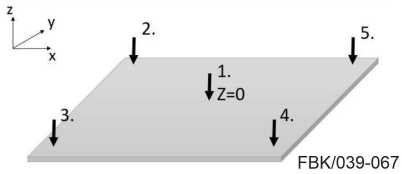

Figure 6: Scheme of measurement for testing distortion using five measuring points.

Consequently, various adjustments were made regarding the experimental procedure to systematically verify the cause of the distortion. First, the following machining strategies were tested:

- Strategy 1: Face milling at RT (roughing and finishing), touching at 2 °C → maximum height difference: 6.7 µm
- Strategy 2: Face milling (roughing) at RT, face milling (finishing) at 2 °C, touching and micro milling at 2 °C → maximum height difference: sample 1: 1 µm/sample 2: 26.7 µm

The maximum height differences determined in these measurements were 6.7 µm and 26.7 µm, respectively, as well as a maximum height difference of 1 µm at the first test strategy 1. Maximum height differences greater than 1.5 µm - 2 µm are unsuitable for micro milling, which meant that subsequent micro milling was possible for only one of the samples.

Subsequently further tests were carried out. These primarily concern adjustments to the experimental setup:

- Adjustment 1: screw attachment stronger and less strong → no influence (Δ < 1 µm)
- Adjustment 2: with and without the shield of the fan → small influence (Δ = 2.7 µm)
- Adjustment 3: warm up the sample to RT and then cool down to 0 °C again → no influence (Δ < 1 µm)
- Adjustment 4: fan switched on and off → no influence (Δ < 1 µm)

The largest maximum height difference measured for 'with and without shield' was 2.7 µm. However, as long as machining is done either with or without shield, there is no significant influence on the distortion. The influence of the other investigated aspects on the distortion can be excluded, because the measured differences are negligibly small.

Neither in the area of the machining strategies nor in the area of the experimental setup a systematic influencing factor for the distortion of the specimen could be identified. However, some factors could be eliminated, as they did not influence the distortion: screw attachment, warm up and cool down the sample, and fan switched on and off.

3.2. Micro milling

Two samples were flat after face milling and were thus suitable for subsequent micro milling. Micro milling of these samples was successful, no tool breakage occurred. After micro milling, confocal microscope images of the micro milled slots were taken with a Nanofocus[1] OEM microscope (60x magnification objective (NA = 0.9)). SEM images (working distance 15 mm; acceleration voltage 20 kV (SE)) were taken to analyze tool wear. Figure 7 shows the results of one of the two samples exemplarily.

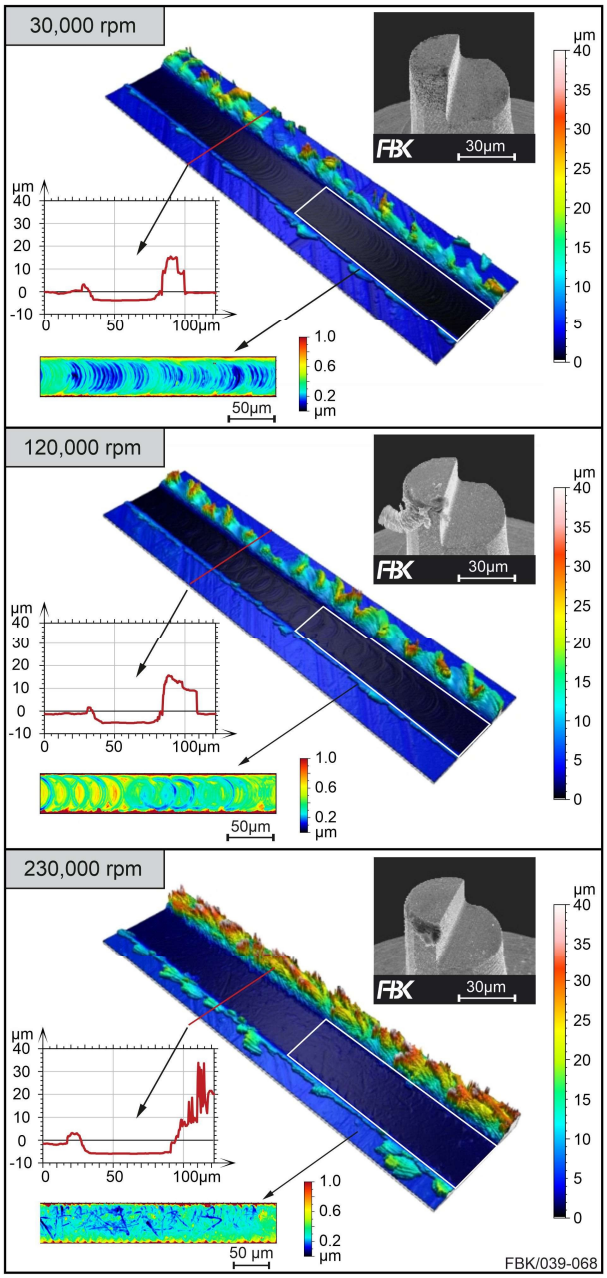

Figure 7: Tool wear, slot shape and slot bottom topography as a function of spindle speed after a feed travel of 1000 mm.

Burr formation is pronounced on the down milling side at all three spindle speeds. Almost no burr is present on the up milling side. Most burr has formed at a spindle speed of 230,000 rpm. At this spindle speed, stars can also be observed at the slot bottom, which indicate strong built-up edge formation [9]. This is probably also the reason for the strong burr formation. At the other two spindle speeds, the kinematic of micro milling can be seen. The 'circles' at a spindle speed of 120,000 rpm at distances of about 20 µm to 30 µm are due to built-up edges that build up and degrades again. The built-up edges can also be seen on the SEM images of the tools taken after the machining process. In general, high tool wear can be observed for all three tools. Compared to the built-up edge formation at 120,000 rpm and 230,000 rpm, a breakout occurred at 30,000 rpm. The tool wear is also reflected in the three sectional views. These show rounded slot edges. In addition, at 230,000 rpm, a significantly larger slot width can be seen due to the built-up edge formation. The slot depth at 120,000 rpm and 230,000 rpm is approx. 5 µm, which corresponds to the depth of cut. At 30,000 rpm, the slot depth is only about 3.4 µm due to strong tool wear (breakout). These results show that if the sample is flat, micro milling under pure process cooling is possible and thus the influence of pure process cooling can be investigated. Challenging, however, is the distortion of the sample, which prevents micro milling when milling with ultra-small micro end mills.

4. Conclusion and outlook

This paper described the design and the characterization of a novel cooling system for micro machining processes. The indirect workpiece cooling was realized through a Peltier element underneath the sample. Additionally, first results were shown when micro milling with 50 µm diameter micro end mills at different spindle speeds.

In further work, the influence of cooling on the micro milling process will be investigated. For this purpose, pure process cooling will be compared to dry machining and the application of metalworking fluids.

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[1] "Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose."

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