Investigations Regarding the Interdependence of Spindle Load and Machine Performance During Slicing

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Abstract: Metal bonded dicing wheels are commonly used for grinding advanced ceramics. But before using such wheels, a preparatory dressing step is necessary to recess the binder and thereby expose the diamond grains. The investigations presented in this paper focused on the wheel’s dressing process for high precision grinding of brittle and hard substrates for MEMS applications. A characteristic value for qualifying the dressing process is the spindle load necessary to drive the dicing wheel. By monitoring the spindle load, changes in the dressing process can be observed. Two types of metal bonded wheels, used in combination with two alternative dressing sticks at various dicing parameters were tested and the influence on the spindle load and on wheel’s surface conditions are investigated.

1. Introduction
Slicing and profiling by outside diameter high precision grinding are standard technologies for the mechanical micromachining of components for micro-electromechanical systems (MEMS) [1]. An important parameter for the characterization of the slicing process is the tangential force between grinding wheel and workpiece. Measuring this force directly is rather difficult; however for high precision outside diameter grinding (“dicing”) machines which are equipped with an air bearing spindle, an indirect approach may be taken: measuring the spindle power and thus the power required to drive the dicing wheel. A variation of the machine parameters or a change of conditions at the dicing wheel led to an alteration of spindle load during the slicing and dressing process. By monitoring the spindle load, changes in the wheel’s condition can be detected. The slicing process parameters can be better understood by investigating the interdependence of spindle load and dicing performance [2].

For grinding hard ceramics, metal bonded wheels are commonly used due to the low wear and their potential for high feed rates. For slicing, a preparatory dressing step of the grinding wheel is necessary [3]. During the dressing step, the binder is recessed and thereby the diamond grains are exposed. The purpose of this investigation is to establish the interdependence between the dressing parameters and the spindle load.

2. Experimental Procedure and Results

2.1. Machine and Workpiece Material
For the investigations a commercial dicing machine was used. It is equipped with a precision air bearing spindle designed for accepting dicing wheels with an outer diameter of approx. 2 inches, air bearing guides of the feed axis and a highly rigid machine body. The spindle’s rotational velocity is up to 40,000 RPM. A feed rate between 0.01 mm/s and 100 mm/s was chosen. The machine’s pitch accuracy, i.e. the accuracy of two parallel dicing cuts, is 0.2 µm. To minimize the environmental influences, the experiments were carried out in a temperature controlled room at 20 °C (+1 °C) [4]. For spindle load measurement, a power measurement system was used. To overcome the substantial limitations of commercial available systems, we developed and built our own system and integrated it in the dicing machine. The measurement principle is to simultaneously determine the power on all three phases driving the spindle motor. The material for the dressing experiments was porous SiC. The stick stick material differ as well as grit size, density, porosity, and hardness.

3. Machining Parameters
For the main experiments two types metal bonded wheels and two alternative dressing sticks were used. Three spindle speeds were chosen: 4,000 min⁻¹, 8,000 min⁻¹, and 12,000 min⁻¹. They were matched with three feed rates: 2 mm/s, 5 mm/s, and 10 mm/s. The cut depth into the dressing stick was 1.4 mm and the dressing length, i.e. the cut length in the dressing stick, was 220 mm. To provide stable initial wheel conditions the wheels were trued in a standard process prior to every experiments.
4. Results

4.1. Influence of Coolant on Spindle Load

Initial tests were performed to determine the influence of the coolant flow on the spindle load. During these tests, the dicing wheel was not engaged in any cutting process. The coolant flow was 0.7 l/min. Figure 1a shows the spindle load without coolant flow. It shows a non-linear increase of the spindle load with a rising spindle speed. At all spindle speeds, a substantial noise was observed which was strongest at 12,000 min⁻¹. This noise is caused by the dicing machine’s inverter. Figure 1b shows a small increase of spindle load due to the coolant flow in the order of 1 to 2 W. The noise also increased slightly in the case of coolant flow. The influence of the coolant flow on the spindle load is negligible and will not be ignored in further examinations.

Figure 1: Spindle load without (a) and with (b) coolant flow

4.2. Interdependence between Dressing Parameters and Spindle Load

Experiments were performed to reveal the influence of feed rate and spindle speed as well as dressing stick and dicing wheel on the spindle load. For these tests the dicing wheels cut two times through the dressing stick with a nominal cut depth of 1.4 mm. Thereby, an overall dressing length of 220 mm was achieved for each test.

Figure 2 shows the spindle load signals during two dressing cuts at a feed rate of 2 mm/s. In Figure 2a a dressing stick A was used, Figure 2b depicts the results for dressing stick B. The overshoot at the beginning of each graph is caused by the transition in spindle load at the rated speed. At low spindle speed, the differences between idle load and dressing load is in the range of the signal scatter. At higher spindle speed a visible difference between dressing load and idle load can be observed.

Figure 2: Spindle load signal stick A (left) and stick B (right) at feed rate of 2 mm/s

Figure 3 shows the net spindle load as a function of wheel, dressing stick, and spindle speed. The net spindle load is obtained by calculating the difference between the mean dressing load and mean idle load. A strong influence of the spindle speed on the net spindle load can be found. Contrary to the influence of the wheel, only small differences in net spindle load between wheel A and wheel B was observed. However, stick A caused significantly higher net spindle loads than stick B.

Figure 3: Net spindle load as a function of wheel, dressing stick, and spindle speed
At a feed rate of 5 mm/s the net spindle load is higher than at low feed rate (Fig 3, right), but similar tendencies can be observed. A strong dependency between spindle speed and net spindle load could be found. The noticeably high net spindle load at 8,000 min⁻¹ for the combination wheel B / stick B resulted from a slightly tilted dressing stick. Thus, the dressing depth grew with increasing dressing length which resulted in a rising spindle load.

![Figure 3: Net Spindle load at a feed rate of 2 mm/s (left), and 5 mm/s (right)](image3)

Similar influences on the net spindle load can be found at a feed rate of 10 mm/s (Fig 4). As observed at the other feed rates, the combination of wheel A / stick A causes the highest net spindle load, and the combination wheel B / stick B generates the lowest net spindle loads, independently of the spindle speed.

![Figure 4: Net Spindle load at a feed rate of 10 mm/s](image4)

### 4.3. Changes in Wheel Conditions

After dressing, the wheels were inspected by scanning electron microscopy (SEM). Figure 5, left reveals the influence of the spindle speed on wheel A’s surface condition when dressed with stick B. At a low spindle speed, the diamond grains were completely covered by the binder material. With increasing spindle speed, the binder was more and more recessed and therefore the diamond grains were exposed. As mentioned above, this wheel / stick combination causes the highest net spindle load.

![Figure 5: SEM images of wheel A and wheel B after dressing](image5)
Investigations of the combination of wheel A and stick B show no influence of the spindle speed on the wheel’s surface condition (Figure 5, right). At all investigated spindle speeds the binder is recessed and the diamond grains are exposed.

An similar result could be found with a combination of wheel B and stick A (Figure 6, left). Independently of the spindle speed, the binding material was recessed by the dressing operation, although the grain concentration was lower and the grain size greater than for wheel A. Figure 6, right shows the results after dressing wheel B with stick B. At low spindle speed the binder is not recessed and therefore the diamond grains are not exposed. At high speed, only a single diamond grain protrudes from the binding material in the left picture.

5. Summary and Conclusions
The executed investigations showed a strong influence of the spindle speed and feed rate on the spindle load. But not only the total spindle load was influenced, the net spindle load (mean dressing load minus mean idle load) depended on theses parameters as well. With rising spindle speed and feed rate both total spindle load and net spindles load increased. The combination of dicing wheel and dressing stick greatly influenced the spindle load, too. While one combination caused generally quite low net spindle loads, another one induced significantly higher net spindle loads (up to factor three higher). By subjecting the wheel after dressing to SEM and analyzing the results, a correlation between net spindle load and wheel’s surface condition could be found. The wheel / dressing stick combination with the highest spindle loads caused the most recessed binder and thereby the most exposed diamond grains on the dicing wheel while the combination with the lowest spindle load induced the least grain exposure.

References