Investigations On the Coolant Supply in Precision Dicing

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Abstract---Outside diameter grinding is used extensively to machine semiconductor materials and advanced ceramics. The cutting grit typically is diamond. If exposed to a temperature exceeding 900°C, it will react with the oxygen in the air and will loose its structural integrity. Therefore, an appropriate cooling is of utmost importance. To analyze the coolant flow, a computational approach to determine the channel available to the cutting zone was compared to actual coolant flow measurements. A relationship between coolant flow and cutting force was established.

I. Introduction

Outside diameter grinding is used extensively to machine semiconductor materials and advanced ceramics [1]. Due to their high Vickers hardness, the cutting grit typically is diamond. During cutting, a substantial amount of heat is created in the contact zone between tool and workpiece. These diamond grains react with oxygen in the air when exposed to a temperature exceeding 900°C [2,3]. Therefore, dicing requires the use of coolant and applying an appropriate amount is therefore essential for achieving optimal grinding results. An investigation was conducted to determine the parameters effecting the otimal coolant flow to the active cutting area.

II. Volume Flow in the Cutting zone

A. Volume Calculation by Geometry Analysis

During dicing, the chip space (V_{cs}) between the grinding wheel and the workpiece, provides space to absorb volume removed (M). It also serves as a coolant delivery path into the cutting zone. A mathematical description of the coolant flow rate Q may be found by describing the chip space available per unit time and subtracting the actual volume of the chips removed. The remaining volume per time interval is available for the coolant flow, establishing the actual flow rate (Q) in the cutting zone. By dividing Q by the cross sectional area A between the dicing wheel, the parameter Q'_A may be derived which describes the amount of cooling supplied to the cutting area in the active gap.

$\dot{M}$ is the volume rate of material removed, it depends on the feed rate (v_f), the wheel depth of cut (t), and the width of the dicing wheel (b) [2]. $\dot{M}$ can be calculated according to equation 1.1 as:

$$\dot{M} = v_f \cdot t \cdot b \qquad (1.1)$$

To determine the actual volume of the chip space, the following method was applied. First, the actual three dimensional work piece surface profile at the bottom of a kerf was determined by white light interferometry. Next the three dimensional wheel profile was measured, also using white light interferometry. As depicted in Figure 1, the chip space volume may be now determined, as long as we make proper assumptions for the diamonds of the wheel profile to be in contact with the ground workpiece profile. Also, since we wanted to calculate a flow rate, the volume was divided by unit time, with the actual volume per time dependent on the dicing wheel's rotational velocity. The chip space per time $\dot{V}_{cs}$ thus equals the volume rate $\dot{V}_{B+D}$ below the wheel section (binder plus embedded diamonds), minus the volume rate above the workpiece surface. The latter one was established by taking the volume rate of the complete measurement area $\dot{V}_{co}$ and substracting the volume rate of the work piece surface profile $\dot{V}_{wp}$.

LIST OF SYMBOLS

A	Cross section	$\dot{V}_{cs}$	Time dependent chip space
M	Volume removed	$\dot{V}_{wp}$	Time dependent volume below the workpiece surface
$\dot{M}$	Volume removal rate	b	With of the dicing wheel
Q	Flow Rate	t	Depth of cut
Q'_A	Flow rate divided by the cross sectional area	n_c	Rotational speed
$\dot{V}_{B+D}$	Volume rate below the wheel section	v_c	Cut speed
$\dot{V}_{co}$	Time dependent complete measuring range	v_{nj}	Nozzle jet velocity
V_{cs}	Chip space	v_f	Feed rate

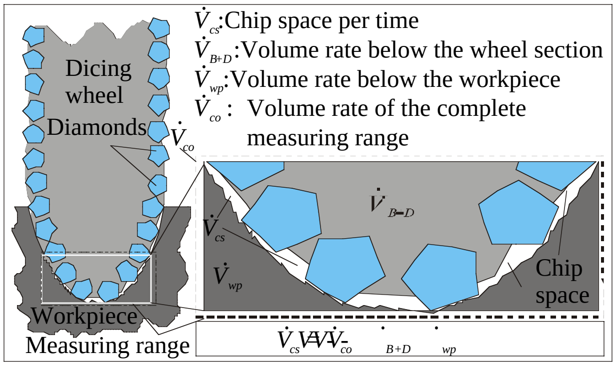

Fig. 1: Cross section of a dicing wheel cutting a workpiece

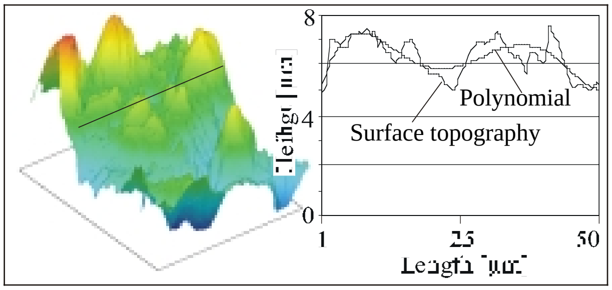

Fig. 2: Cross sectional approximation during dicing wheel volume commutation

To allow a statistical evaluation the measurements were repeated on 20 different dicing wheel locations. The data compounded were saved in ASCII format for the numerical volume calculation. These data represent the individual measurement series which were recorded during the white light interferometry measurements. A program developed specifically for this application allowed a separation of the data stored. The volume defined by the topography measurements was then determined using two alternative methods.

The first method analyzed the respective measurement series individually and independently from each other. To do so, a polynomial, which approximates each one of the series, was calculated by applying the Gaussian interpolation method (Fig. 2). The resulting data allowed to determine the volume integral of the space below the surface described by the polynomials. Consecutively, the total result was computed by summing up the individual calculation results.

The second method made use of the FEM program Advanced Visual Systems (AVS) to do the calculations required. The program allowed to calculate the volume enclosed below a surface topography. A comparison of both results showed a good agreement between both calculation methods.

Once $\dot{V}_{cs}$ was calculated and, assuming that the entire chip space is available for the coolant as well as the chipping products, Q'_A was determined according to equation 1.2. A represents the contact area between the dicing wheel and the work piece.

$$Q'_A = (\dot{V}_{cs} - \dot{M}) / A \tag{1.2}$$

B. Volume Measurement by Experimentally Determining the Coolant Flow

The conventional approach to determine the volume flow is to use a guide blade immediately behind the wheel to collect the coolant. The guide blade diverts the used coolant directly into an external container for volume measurement. However, for small dicing wheels with a wheel width below 300 µm, this method proved to be unsuitable. A puddle of coolant is forming around the gap during the dicing process as the coolant is diverted sideways, thus falsifying the test results. Furthermore, the flanges holding the dicing wheel tend to cause coolant to swirl greatly, allowing coolant following the wheel outside the gap to reach the guide blade. To achieve more accurate results, a method was devised which collects the coolant directly at the cutting zone. Figure 3 shows the schematics of the approach taken: a workpiece holder was equipped with a groove with a progressive depth. A bore in the groove serving as an exit orifice was connected to an external duct. The duct consisted of a transparent plastic tube allowing to observe the presence of air bubbles. A groove was ground into the workpiece, then it was glued to the workpiece holder with boths channels formed by the respective grooves lining up. During a consecutive test cut, the groove was cut open which then allowed to collect the coolant flowing through the cutting zone.

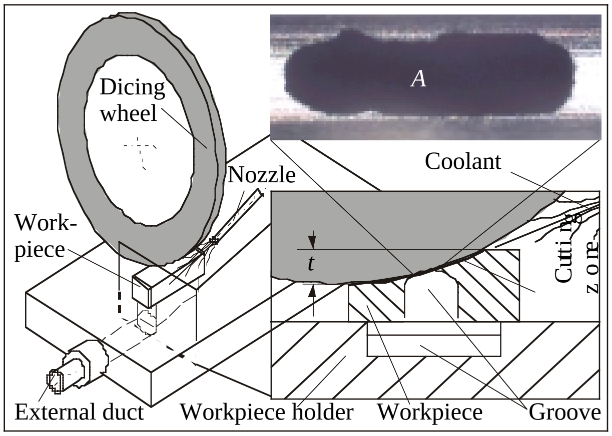

Fig. 3: Schematic representation of the devise set up to measure the coolant flow in the cutting zone

Previously to executing the test cut, the position was calculated at which a kerf would intersect with the groove and would form a predetermined cross section. During a test, the rotating dicing wheel was fed to the calculated position and, by doing so, the upper cut in the workpiece was executed. Due to the continuous coolant flow, the coolant passing through the cutting zone was redirected into the lower groove and collected through the exiting tube while measuring the coolant flow per time. The coolant flow in the cutting zone was smaller than 0.01 ml per cutting pass. For that reason, the measurement was better suited for static tests and therefore was executed at zero feed rate ($v_f = 0$). To avoid errors due to workpiece motion, the calculated workpiece position was maintained throughout the tests.

C. Comparison of the Theoretical and Experimental Results

Figure 4 depicts a comparison of Q'_A determined by numerical calculation and through coolant flow experiments in the cutting zone for two different dicing wheels in a worn state. The chosen cut speed applied for the experimental investigations was matching the time base chosen during the numerical calculation.

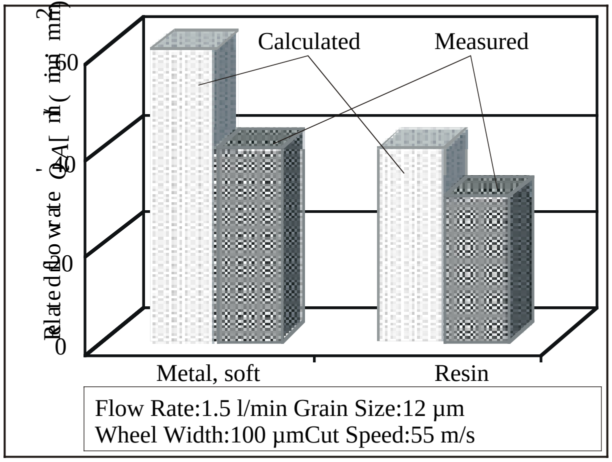

Fig. 4: A comparison between the calculated and the measured related flow rate in the cutting zone

For a soft metal bonded wheel a Q'_A of 60 ml/(min.mm^2) was calculated while a resin bonded wheel resulted in a Q'_A of 38 ml/(min.mm^2). The reason may be found in diamond grains with a higher protrusion breaking off the relative porous resin binder which leads to a smaller chip space.

Experimental data for the actual fluid flow were appr. 37 ml/(min.mm^2) for a metal bonded wheel and 24 ml/(min.mm^2) for a resin bonded one. For these tests, the coolant supply rate was 1.5 l/min. This correlates to appr. 60% of the calculated amount. The difference between the numerically and the experimentally determined Q'_A values may be attributed to the flow characteristics of the coolant jet (laminar, which is desirable, or turbulent), the adhesion of the coolant at the interface between wheel and workpiece fringe areas, as well as to the coolant backflow. An increase of the volume flow rate into the cutting zone, and therefore an approximation towards the theoretical value, may be accomplished by modifying the coolant nozzles' jets. Areas of improvement for coolant nozzles are a reduction of the pressure drop and avoiding turbulence in the coolant jet.

In operation ($v_f > 0$mm/s) $\dot{V}_{co}$ not only contains coolant but also chips. As a for instance the volume flow for a feed rate of 1 mm/s and a cut depth of 1 mm relates to a material volume rate of 1.0*10^8 µm^3/s. This amount roughly represents only 2% of the calculated time related volume of the available chip space.

III. Relative Velocity between Dicing Wheel and Nozzle Jet

During cutting, the rotating dicing wheel transports the coolant into the cutting area. Therefore, the magnitude of Q'_A depends among other on the cutting speed [2]. Figure 5 depicts the relative velocity between the dicing wheel and the nozzle jet (v_c/v_{nj}) as a function of the rotational velocity (n_c) and the relative volume flow Q'_A. The figure shows clearly an increase of Q'_A with decreasing v_c/ v_{Nj}. Due to the fact that the nozzle jet velocity (v_{nj}) is limited, the pressure drop at the nozzles, v_c/ v_{nj} decreases when v_c increases. Therefore, the actual coolant flow decreases with increasing rotational velocity. This issue may be addressed by modifying the jet nozzles in a controlled fashion. Also, it was observed that the exit tube showed air bubbles indicating the presence of air in the cutting zone.

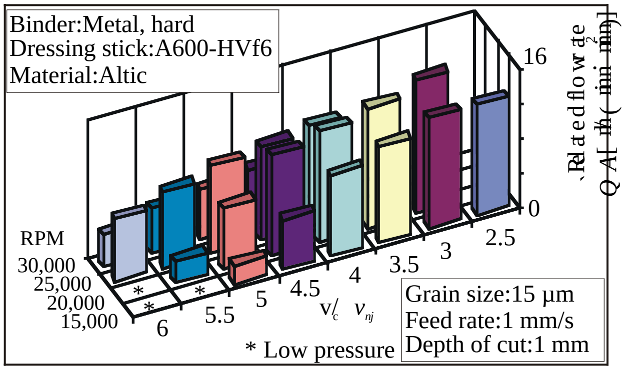

Fig. 5: Q'_A as a function of the velocity between the dicing wheel and the nozzle jet

In case of too low a coolant velocity, a negative pressure is forming in the cutting zone, preventing coolant from reaching the cutting zone. This phenomenon is caused by the rotating wheel being surrounded by an air cushion due to frictional effects, which mainly depend on the wheel's surface roughness [4]. This air cushion is forming a barrier in front of the dicing wheel, preventing the coolant to enter the cutting zone.

IV. Cutting Performance under Improved Coolant Supply Conditions

By appropriately modifying the nozzle design, a compact coolant jet showing laminar flow over a long distance could be achieved. The effect of such an optimized coolant jet on the cutting results was verified by measuring the cutting forces. Figure 6 depicts the tangential forces for resin bonded wheels as a function of the nozzle jet velocity. Using the modified nozzle resulted in a reduction of the cutting forces. Such an optimal coolant flow may be expected to positively influence the cutting process in multiple ways. The two most important effects were expected to be an optimal heat transfer [5] which kept the diamonds sharp and a reduction of friction due to the fluid film. Both are reducing wheel wear and workpiece subsurface damage due to thermal load. Furthermore, an optimal coolant supply also results in the cleaning of cutting chips from the dicing wheel, further reducing the pressure between dicing wheel and workpiece in the cutting area. While a breakdown of the influence of the various effects was not attempted during this work, the relationship between coolant supply and cutting force clearly emphasizes the importance of an appropriate coolant supply.

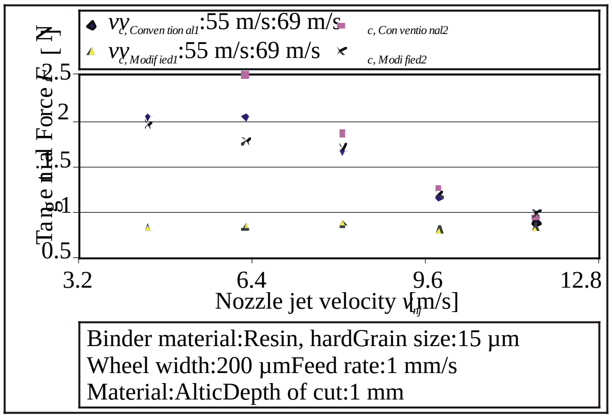

Fig. 6: Tangential cutting force as a function of the nozzle jet velocity

V. Conclusion

By comparing a computational approach of determining the cutting zone with coolant flow measurements, the effectiveness of a coolant supply could be judged. The computational approach was based on numerical surface analyses data based on white light interferometry measurements. For the experimental approach, a measurement system was devised allowing to pick up the coolant flow directly at the cutting zone, thus avoiding errors in measuring the actual coolant flow rate typical for conventional systems.

It could be proven that a compact coolant jet with laminar flow substantially contributes to achieving an optimal cutting process. Most desirable is a nozzle creating a compact jet maintaining a laminar flow over a distance as great as possible. It further coud be proven that such a coolant system substantially reduces the cutting forces and wheel wear. The reduction was attributed to better heat transfer, lower friction at the effective cutting area, and better cleaning off the chips from the dicing wheel.

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