Grain flash temperatures in diamond wire sawing of silicon

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Abstract

Diamond wire sawing has obtained 90% of the single-crystal silicon-based photovoltaic market, mainly for its high production efficiency, high wafer quality, and low tool wear. The diamond wire wear is strongly influenced by the temperatures in the grain-workpiece contact zone; and yet, research studies on experimental investigations and modeling are currently lacking. In this direction, a temperature model is developed for the evaluation of the flash temperatures at the grain tip with respect to the grain penetration depth. An experimental single-grain scratch test setup is designed to validate the model that can emulate the long contact lengths as in the wire sawing process, at high speeds. Furthermore, the influence of brittle and ductile material removal modes on cutting zone temperatures is evaluated.

Keywords Flash temperature · Silicon · Wire sawing · Single-grain scratching · Wear

1 Introduction

In mechanical material removal, the highest share of the input energy is transformed to thermal energy [1]. Kennedy [2] states that 95% of the energy dissipation happens in the top of the bodies in contact, and according to Kato [3], virtually all of this energy is converted to heat at the grain-workpiece interface. The energy created during the short contact time leads to high temperatures at the grain, called the flash temperatures [4]. In grinding, the time of contact of a grain with the workpiece is in the range of 1 µs; hence, the interaction can be defined as near-adiabatic. However, in diamond wire sawing, the presence of long contact lengths emphasizes the influence of temperature effects.

Diamond wire sawing is a process predominantly used to slice hard and brittle material into wafers. In recent years, wire sawing with fixed grains has evolved to replace wire sawing with slurry due to advantages like lower kerf loss, higher material removal rate, and superior wafer strength [5]. Single-crystal silicon (Si) wafers for semiconductor

and photovoltaic applications are typical applications that feature very long contact length of traditionally 156 mm, while the trend for solar cells is to increase the wafer size to 210 mm and possibly up to 300 mm in the future.

Temperatures in the cutting zone have great influence on the grain wear. Wear models such as those proposed by Takeyama and Murata [6], Usui et al. [7], and Jiang and Arnell [8] predict a dependence of wear on the contact temperature. During turning of Si with diamond tools, carbon diffuses into the Si surface to form hard silicon carbide (SiC), which consequently leads to heavy tool wear on the flank face [9]. The formation of SiC and diamond-like carbon structures on the Si surface is accelerated by high temperature and pressure. Formation of SiC was not observed in diamond scratching with an engagement length of 20 mm, a depth of cut of 10 µm, and a low cutting speed of 100 mm/min [10]; a possible explanation lies in the interruption of the diffusion process with brittle fracture and the short contact length. Analysis of worn wires used to cut 156-mm Si ingots with 15 m/s showed graphitic phases on 3 out of 21 diamonds analyzed [11].

The workpiece surface quality is also affected by the cutting temperature. While it was shown that the coolant has a significant effect on the wafer temperature field [12], temperatures in the contact zone are typically much higher than the boiling temperature and therefore have little effect on the temperature in the cutting zone [13]. Lindholm et al. [14] have studied the coolant temperature rise during wire sawing of multi-crystalline silicon and have simulated the temperature change during the cut along with the resulting

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Table 1 Nomenclature used in the study (formula symbols only)

Symbol	Meaning	Unit
κ_w	Thermal diffusivity of silicon	$[m^2/s]$
ρ_g	Material density of diamond	$[kg/m^3]$
ρ_w	Material density of silicon	$[kg/m^3]$
$A_{\perp}$	Orthogonal grain area normal to the workpiece surface	$[\mu m^2]$
A_{cu}	Penetrated grain area projected into direction of cut	$[\mu m^2]$
C_p^g	Specific isobaric heat of diamond	$[J/kg K]$
C_p^w	Specific isobaric heat of silicon	$[J/kg K]$
F_c	Cutting force	$[N]$
h_{cu}	Grain penetration depth, undeformed chip thickness	$[\mu m]$
h_g	Grain height	$[\mu m]$
k_c	Specific cutting force (empirically determined)	$[N/mm^2]$
k_b	Thermal conductivity of nickel (bonding material)	$[W/m K]$
k_g	Thermal conductivity of diamond	$[W/m K]$
k_w	Thermal conductivity of silicon	$[W/m K]$
l_g	Grain length	$[\mu m]$
m_c	Cutting force model exponent (empirically determined)	$[-]$
Pe	Peclet number	$[-]$
$\dot{q}_g$	Heat flux to the grain	$[W/m^2]$
$\dot{q}_t$	Total heat flux	$[W/m^2]$
$\dot{q}_w$	Heat flux to the workpiece	$[W/m^2]$
t	Time	$[s]$
T	Temperature	$[K]$
T_b	Temperature of the bonding material	$[K]$
T_f	Flash temperature at the grain tip	$[K]$
v_c	Cutting speed	$[m/s]$
v_{rel}	Relative sliding velocity	$[m/s]$
w_g	Grain width	$[\mu m]$

effects of thermal expansion. Depending on the cooling conditions, the heat generation between the wires and the silicon block has been determined to lie between 0.28 and 0.43 W/mm, leading to temperatures in the material of up to 270 °C in the beginning of the cut. Thermal deflection of the wafer along the wire direction of up to 10 μm may have

a deteriorating effect on the total thickness variation of the wafer.

Temperature measurement in grinding processes is generally possible by measuring conducted or radiated heat [15], where methods using heat conduction typically apply thermocouples and methods measuring radiation

Fig. 1 **a** Overview of the scratch test setup. **b** Details of the pin and the position of the wire. **c** Alicona IFM image of the isolated grain on pin tip and fiber of the pyrometer

Fig. 4 **a** Alicona IFM image of an abrasive grain on pin tip. **b** Grain cross sections orthogonal and normal to the cutting direction

The setup is mounted on a Fehlmann Versa 825 5-axis milling machine. This machine fulfills requirements regarding stiffness and spindle speed required for the conduction of the experiment; the HSK63 spindle interface is suitable to hold an adapter clamping the heavy Si workpiece and safely fixing it at high spindle speeds. The force measurement system is composed of a Kistler MiniDyn Type 9256C1 3-component force dynamometer, Kistler Type 5080A charge amplifier, National Instruments NI 9222 analog-to-digital converter, and a measurement laptop with Labview software. A Fire-3 two-color fiber optic pyrometer is used to measure the temperatures. No coolant is applied. Optical measurement of the grain and the workpiece surface are performed using an Alicona Infinite Focus G4 microscope (IFM).

The cutting kinematics and the coordinate system are defined in Fig. 2. The contact is described from the viewpoint of point P on the grain tip which is assumed to be moving over the cutting path instead of workpiece rotation. Both approaches represent the identical kinematic conditions, while the former serves simplicity of the explanation. The grain starts its motion with zero penetration at point K and moves with an angular velocity ω in clockwise direction. The grain is advanced onto the surface with the vertical feed rate v_{fz} ; and the radial feed rate v_{fr} dictates the distance C between two consequent scratches.

Figure 3a shows the lapped and polished, mirror-like Si workpiece surface with a maximum profile height of $R_z = 0.49 - 0.52 \mu\text{m}$ determined in accordance with DIN EN ISO 4287 [23]. The material used is commercial solar-grade monocrystalline Si. In Fig. 3b, an Alicona IFM image of multiple scratches on the workpiece surface is presented.

Each identified section shows passes by the same grain and consists of several consequent scratches with increasing penetration depth. The exact penetration depth cannot be controlled because of a slightly irregular concave shape of the workpiece surface. The penetrated depth or undeformed chip thickness h_{cu} is estimated from the residual scratch depth according to the methods described in [24]. A continuous contact between the grain and Si workpiece is not possible due to a small perpendicularity error of the workpiece surface with the spindle axis; instead, a section of the surface is scratched where the contact length of one grain pass is 40 mm and the average total contact distance of a grain is 0.8 m. The cutting time is determined from the measured force signal. Both ductile and brittle material removal can be observed and associated with the respective forces and temperatures.

Figure 4a shows the top view of the Alicona IFM image of an isolated abrasive grain on the pin tip. Figure 4b shows the grain cross sections parallel and orthogonal to the cutting direction. The grain protrusion h_g is measured from the surface of the wire. The grain penetration depth of h_{cu} and cutting area A_{cu} are shown. The grain wears over the course of the experiment, and its protrusion decreases by $0.5 - 1.5 \mu\text{m}$. The ratio of cutting area to penetration depth A_{cu}/h_{cu} is more or less constant when comparing the grain before and after the cut, implying that the grain wears out regularly in terms of the shape projected into the cutting plane, even though the cutting edge rounds off during the cut. The typical wear behavior of a single diamond grain in contact with Si has been analyzed in the past [25].

For this work, flash temperatures at the grain tips that are measured during the scratch tests are evaluated. Flash temperatures from a series of scratches performed with

Fig. 5 Voltage readings from two pyrometer wavelengths

individual grains are measured. Figure 5 shows the voltage readings of two different wavelengths where each peak corresponds to a single scratch. The beginning and end of the contact are identified from the voltage signal; a threshold value of 0.1 V is applied.

The temperature values corresponding to the presented wavelengths are shown in Fig. 6. The raw measurement data is presented on top, where a very high noise-to-signal ratio necessitates the definition of the beginning and end of the scratch from the voltage signal. Figure 6b and c show isolated and typical temperature readings associated with a brittle (b) and ductile (c) scratch.

3 The flash temperature model

The problem of flash temperatures at the grain tip can be described as the distribution of the energy produced in the contact area through relative sliding of the grain and workpiece. The total heat generated Q_t is distributed as Q_g conducted to the grain, Q_w to the workpiece, Q_{ch} to the chip, and Q_f to the coolant. However, the share of heat extracted by the chips is limited [26] and much smaller in comparison to the heat conduction into the grain and workpiece; hence, Q_{ch} can be neglected. Moreover, in the contact region, the temperatures are far higher than the coolant boiling temperature, limiting the convection effects in the cutting zone [13]. The effect of the cooling fluid is hence restricted to cooling of the tool outside the contact region [27]. The total heat rate generated per unit area $\dot{q}_t$ is then shared between the grain and workpiece:

$$\dot{q}_t = \dot{q}_g + \dot{q}_w \quad (1)$$

where $\dot{q} = Q_t/A_\perp$, and $A_\perp$ is the orthogonal grain area in the direction normal to the workpiece surface. The total heat rate generated is:

$$\dot{q}_t = \frac{F_c \cdot v_{rel}}{A_\perp} \quad (2)$$

Fig. 6 **a** Plot of the raw temperature data. **b** Measured temperatures of an individual brittle scratch. **c** Measured temperatures of an individual ductile scratch

where the cutting force F_c is acting on the grain parallel to the relative sliding velocity v_{rel} .

The problem is then reduced to the determination of the share of the produced heat to the workpiece and to the diamond grain. The condition on the workpiece side can be defined as a stationary heat source on a moving body, as schematically described in Fig. 7. The heat source (grain) is stationary with the origin of the fixed coordinate system (x, y, z) and the semi-infinite body is sliding at $z = 0$ with a constant velocity v_{rel} with the coordinate system (x', y', z') attached to its body.

A significant simplification of the heat conduction problem is to assume steady-state heat flow instead of a transient condition. The time frames until the steady-state conditions are reached were studied by Bhushan [28], to find that the flash temperature reaches its steady state after a sliding distance of 1.25 times the length of the source. Furthermore, for a moving circular heat source, Yevtushenko [29] stated that the temperature at the contact zone reaches 87% of its steady almost instantly. The transient conditions were studied by Jaeger [22] in the

Fig. 7 Dimensions and definitions of the grain-workpiece contact conditions

case of a moving square heat source over a surface. The time until steady state is reached can be described by the nondimensional Peclet number. The times at which the temperature reaches steady-state condition are plotted in Fig. 8a. The Peclet number for square and band sources is defined as:

$$Pe = \frac{v_{rel} \cdot (l_g/2)}{2 \cdot \kappa_w} \quad (3)$$

where l_g is the length of the contact surface in the sliding direction, $l_g = w_g$ is assumed in Fig. 7, and κ_w is the thermal diffusivity of Si, defined as:

$$\kappa_w = \frac{k_w}{\rho_w \cdot C_p^w} \quad (4)$$

where k_w is the thermal conductivity, ρ_w is the density, and C_p^w is the specific isobaric heat of Si.

The primary assumptions of the temperature model are:

- Contact and penetration area between the grain and the workpiece remain constant over the contact time
- Diamond and silicon have constant and temperature-independent material properties
- Heat extraction due to coolant and chip is negligible
- No heat exchange between the grain and the surroundings

- No internal heat generation, especially negligible heat generation due to plastic dissipation during chip formation
- Steady-state heat flow in the diamond
- Constant bonding material temperature

The solution for a square uniform band heat supply acting on a semi-infinite solid surface is defined by Carslaw and Jaeger [21] and the results are plotted in Fig. 8b, which are highly dependent on the Peclet number.

For $Pe \leq 10$ and a uniform band source heat distribution, the maximum flash temperature rise ΔT_f is approximated by Tian [30] as:

$$\Delta T_f = \frac{2 \cdot \dot{q}_w \cdot (l_g/2)}{k_w \sqrt{\pi(1 + Pe)}} \quad (5)$$

where k_w is the thermal conductivity of silicon, Pe is the Peclet number defined for the relative sliding speed, and l_g is the grain side length orthogonal in the direction of sliding.

One-dimensional heat conduction towards the bonding surface with constant material parameters is assumed for the grain:

$$\frac{\partial T}{\partial t} = \frac{k_g}{\rho_g \cdot C_p^g} \frac{\partial^2 T}{\partial x^2} \quad (6)$$

It is required to define the initial and boundary conditions to solve the equation. Based on Fig. 9, in the case of a steady-state, linear, one-dimensional heat transfer in a column, the initial and boundary conditions (IC and BC respectively) can be stated as:

$$B.C.^1: \quad \text{at } x = 0 \quad \dot{q} = -k_g \frac{\partial T}{\partial x} \quad (7)$$

$$B.C.^2: \quad \text{at } x = h_g \quad \dot{q} = -k_g \frac{\partial T}{\partial x} = -k_b (T_{x=h_g} - T_b) \quad (8)$$

Fig. 8 **a** Temperatures at the surface of a square heat source sliding with a constant velocity as a function of time and Peclet number [22]. **b** Temperature behavior on a semi-infinite solid, resultant of a sliding of a surface with width $2b$ [21]

Fig. 9 Parameters of the grain model and the direction of heat flow

The temperature distribution as a function of distance from the grain tip is then defined as:

$$T(x) = \frac{T_b - T_f}{h_g}x + T_f \quad (9)$$

The rate of heat flow per unit area is found:

$$\dot{q}_g = k_g \frac{(T_f - T_b)}{h_g} \quad (10)$$

Combining Eqs. 1, 2, 5, and 10, the flash temperature at the grain tip can be calculated:

$$T_f = \frac{k_{c1} \cdot A_{cu}^{1-m_c} \cdot 2 \cdot (l_g/2) \cdot h_g}{k_g \cdot A_{\perp} \cdot 2 \cdot (l_g/2) + k_w \cdot A_{\perp} \cdot h_g \sqrt{\pi(1 + Pe)}} \quad (11)$$

where k_c is the specific cutting force and m_c is the material-pair dependent constant, which are experimentally determined for diamond and single crystal Si (sc-Si) [24]. Properties of sc-Si and synthetic single crystal diamond are listed in Table 2.

4 Results and discussion

A useful observation is presented in Fig. 6b and c, where measured temperatures of representative brittle and ductile scratches are depicted. In both graphs, the grain starts its penetration from the left side and the contact ends at the right side of the plot. The middle part of the plot shows the state at the maximum grain penetration. In the case of brittle material removal, as the penetration depth increases, the rate of fracture increases, the energy is dissipated with fracture, and lower temperatures are measured at the grain tip. In the ductile material removal case, a higher share of

energy is dissipated in the form of thermal energy, leading to a temperature increase as the grain penetration increases.

Model validation experiments are conducted with 6 grains and 90 scratches in total, at the cutting speed of 10 m/s. The comparisons of the simulated and measured results show that the model underestimates the flash temperature T_f by a factor of ≈ 4.5 . While this factor may seem large, it can be explained through consideration of the most significant simplifications adopted in the model:

- The contact between the grain and the workpiece material $A_{\perp}$ is not rectangular and largely overestimated in the model. Figure 10 shows a point cloud representation of a grain used in the experiments. The vertices on the grain surface that are in contact with material during a scratch are marked as red dots while the model assumption of a square contact based on the width of the grain in contact is shown as a red square. There is a significant deviation between the assumption and the real observation, where the area assumed in the model is between 1.5 and 2.5 times larger than the area based on the real contact geometry. The larger contact area $A_{\perp}$ reduces the modelled flash temperature according to Eq. 11.
- $\dot{q}_g$ is overestimated in the model. This is due to the assumption that the temperature of the bonding T_b is equal to the ambient temperature, operating as a heat sink. This is clearly not the real case, where it is expected that the heat flow from the grain tip to the bonding material shall result in a background temperature rise on the wire, leading to a decrease in the temperature difference and reduction in the rate of heat flow. A reduced heat flow through the grain will increase the flash temperature.
- The assumption that all heat introduced into the diamond stems from the sliding contact is another significant deviation from reality. For this model, the total heat generated is assumed to equal $Q_t = F_c \cdot v_{rel}$. This relationship obviously neglects all effects of the significantly larger normal force F_n exerted onto the surface and therewith associated with plastic deformation. It is generally assumed that the ratio of dissipated heat to plastic work (known as the Taylor-Quinney coefficient β) is a constant and has a value of 0.9, while it has been shown that it depends on the material and on strain and strain rate for steels [33].

Table 2 Thermal properties and densities of sc-Si and Type IIa single-crystal diamond at 300 K

	sc-Si [31]	Diamond [32]
Density ρ [kgm^{-3}]	2329	3520
Specific isobaric heat C_p [$Jkg^{-1}K^{-1}$]	713	502–519
Thermal conductivity k [$Wm^{-1}K^{-1}$]	156	2000–2100

Fig. 10 Contact area between a grain and the workpiece at a penetration depth of $h_{cu} = 570\text{nm}$; point cloud representation of the microscopic image of a grain used in the experiments with vertices in contact shown in red and the respective model assumption of a square contact shown as red rectangle

The Taylor-Quinney coefficient for Si is unknown, but since plasticity is observed during the cutting of silicon especially in ductile cutting, it is likely that it is a substantial heat source that is neglected in the model.

The flash temperature is simulated using geometric data of the grains used in the experiments. The simulated flash temperature is multiplied with a constant coefficient of 4.5 to compensate the abovementioned underestimation. Through substituting the penetration area with the integral of the grain width over the penetration depth, $A_{cu} = \int_0^{h_{cu}} w_g(z) dz$ in Eq. 11 gives the flash temperature value as a function of the grain penetration depth h_{cu} . The comparison of the measured and simulated flash temperatures is plotted in Fig. 10 as a function of the grain penetration depth. The results suggest that the flash temperature values decrease with increasing penetration,

showing that grains cutting in the brittle removal regime result in slightly lower temperature values.

The data fit shown in Fig. 11 predicts very high temperatures exceeding 2000 K at very low penetration depths. The validity of the model and the fit for low penetration depths cannot be discussed with the experimental results since no observations for a penetrated depth lower than 500 μm are available. Since low penetration depths are accompanied by small contact areas; the diamond volume is relatively larger in comparison with the contact area and therefore has a relatively higher heat capacity. Heat generated in the sliding zone may therefore be distributed into the diamond more efficiently leading to overall lower flash temperatures than the model predicts. This may however be counteracted by the increasing heat generation due to plastic deformation associated with ductile removal at low cutting depth.

Fig. 11 Comparison of the measured temperatures at single-grain scratch test and simulation results of the flash temperature model using Eq. 11

With increasing velocity, the Peclet number increases (see Eq. 3) and the workpiece surface temperature decreases in case of constant heat generation. Hence, at higher cutting speeds, where $Pe \leq 10$, lower flash temperatures may be observed.

Last, it should be noted that consecutive scratches with the same grain lead to geometrical deviations due to wear as described in Section 2. The deviations are not considered in the calculation of the simulated data points. Wear may affect the width of the grain at a given penetration depth, which leads to an underestimation of the grain width as grains are typically tapered. Limitations of the experimental rig, where individual grains have to be isolated manually at the top of the pin, lead to a selection of large and blocky grains in the experiments. Analysis of the worn grains has shown that the ratio of the width to penetrated depth remains more or less constant.

Many recent approaches to modelling the workpiece surface quality in diamond wire sawing and grinding processes in general are based on the interaction between the workpiece and individual grains [34–36]. With improved methods and increasing computation power, larger surfaces can be simulated and improvement of the prediction requires the consideration of wear. The incorporation of a temperature model, which is able to predict temperature based on the contact geometry and the cutting velocity, is necessary to accurately model wear. Such a holistic approach has recently been presented [24].

5 Conclusion

Experiments with solar-grade monocrystalline Si and diamonds electroplated onto commercial diamond wire as used in industrial diamond wire sawing applications have been conducted to study the flash temperature. For this purpose, a new test setup is introduced. In dry cutting conditions and for a contact length of 40 mm and cutting speed of $v_c = 10$ m/s, flash temperatures exceeding 1500 K have been observed.

A model for the calculation of flash temperatures when cutting Si with diamond has been derived and validated with experiments. The model considers heat flux in the diamond grain and binder, a heat source due to a sliding contact described by the tangential cutting force, and the sliding velocity through the Peclet number. Including a force model allows for the determination of flash temperature based on the cutting speed, the grain geometry, and the penetrated depth. This relationship may be used for kinematic process models for the diamond wire sawing process.

The flash temperature model and the experiments show that at lower depths of cut, with the presence of ductile material removal mode, high temperature is present at

the grain tip. Moreover, as long as the ductile material removal is present, an increase in the depth of cut results in higher temperatures. As the depth of cut increases, material is removed in a more brittle regime, resulting in lower temperatures.

An empirically determined constant is necessary to compensate for deviations due to the simplifications adopted in the model development. For the assumptions employed, the constant has been determined as 4.5.

The model can be improved especially through the consideration of a more realistic contact area and modelling transient heat flow in the grain due to initial heating of the grain and with increasing binding temperature resulting from heat transfer to the wire. Further improvements may be achieved by taking heat generation through plastic deformation in the workpiece material into account.

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S. Süssmaier: conceptualization, planning, and conduct of experiments, surface measurement, editing of the manuscript.

K. Wegener: conceptualization, supervision, review and editing of the manuscript.

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Declarations

Consent for publication All the authors consent to publishing the present study.

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References

- Tönshoff HK, Peters J, Inasaki I, Paul T (1992) Modelling and simulation of grinding processes. *CIRP Ann* 41(2):677–688. [https://doi.org/10.1016/S0007-8506\(07\)63254-5](https://doi.org/10.1016/S0007-8506(07)63254-5)
- Kennedy FE (1982) Single pass rub phenomena—analysis and experiment. *J Lubr Technol* 104(4):582–588. <https://doi.org/10.1115/1.3253293>
- Kato T, Fujii H (1998) Temperature measurement of workpieces in conventional surface grinding. *J Manuf Sci Eng* 122(2):297–303. <https://doi.org/10.1115/1.538918>
- Archard JF (1959) The temperature of rubbing surfaces. *Wear* 2(6):438–455. [https://doi.org/10.1016/0043-1648\(59\)90159-0](https://doi.org/10.1016/0043-1648(59)90159-0)
- Kumar A, Melkote SN (2018) Diamond wire sawing of solar silicon wafers: a sustainable manufacturing alternative to loose abrasive slurry sawing. *Procedia Manufacturing* 21:549–566. <https://doi.org/10.1016/j.promfg.2018.02.156>
- Takeyama H, Murata R (1963) Basic investigation of tool wear. *J Eng Industry* 85(1):33–37. <https://doi.org/10.1115/1.3667575>
- Usui E, Shirakashi T, Kitagawa T (1978) Analytical prediction of three dimensional cutting process—part 3: cutting temperature and crater wear of carbide tool. *J Eng Industry* 100(2):236–243. <https://doi.org/10.1115/1.3439415>
- Jiang J, Arnell RD (1998) The effect of sliding speed on wear of diamond-like carbon coatings. *Wear* 218(2):223–231. [https://doi.org/10.1016/S0043-1648\(98\)00202-6](https://doi.org/10.1016/S0043-1648(98)00202-6)
- Zong WJ, Sun T, Li D, Cheng K, Liang YC (2008) Xps analysis of the groove wearing marks on flank face of diamond tool in nanometric cutting of silicon wafer. *Int J Mach Tools Manuf* 48(15):1678–1687. <https://doi.org/10.1016/j.ijmachtools.2008.06.008>
- Kumar A, Melkote SN (2018) Wear of diamond in scribing of multi-crystalline silicon
- Yang JT, Banerjee S, Wu JN, Myung Y, Rezvanian O, Banerjee P (2016) Phase and stress evolution in diamond microparticles during diamond-coated wire sawing of silicon wafers. *Int J Adv Manuf Technol* 82(9–12):1675–1682. <https://doi.org/10.1007/s00170-015-7446-y>
- Huang XR, Huang H, Guo H (2019) Simulation and experimental research on the slicing temperature of the sapphire with diamond wire. *International Journal of Computational Methods*. 16(4). <https://doi.org/10.1142/S021987621843003x>
- Howes TD, Neailey K, Harrison AJ, McKeown PA (1987) Fluid film boiling in shallow cut grinding. *CIRP Ann* 36(1):223–226. [https://doi.org/10.1016/S0007-8506\(07\)62591-8](https://doi.org/10.1016/S0007-8506(07)62591-8)
- Lindholm D, Mortensen D, Fjaer H, Yan SJ, Song A, Tan AL, Chua NT (2018) A computer model and methodology to predict temperatures and deformations during diamond multi-wire cutting. *Silicon* 2018: The 8th International Conference on Crystalline Silicon Photovoltaics 1999(1):140002. <https://doi.org/10.1063/1.5049341>
- Tönshoff HK, Friemuth T, Becker JC (2002) Process monitoring in grinding. *CIRP Ann* 51(2):551–571. [https://doi.org/10.1016/S0007-8506\(07\)61700-4](https://doi.org/10.1016/S0007-8506(07)61700-4)
- Ueda T, Hosokawa A, Yamamoto A (1985) Studies on temperature of abrasive grains in grinding—application of infrared radiation pyrometer. *J Eng Industry* 107(2):127–133. <https://doi.org/10.1115/1.3185975>
- Akbari M, Kluev M, Boos J, Wegener K (2018) Temperature and force measurements in single diamond scratch tests. *Int J Adv Manuf Tech* 96(9):4393–4405. <https://doi.org/10.1007/s00170-018-1930-0>
- Vinay PV, Srinivasa Rao C (2015) Temperature assessment in surface grinding of tool steels. *J Mech Sci Technol* 29(11):4923–4932. <https://doi.org/10.1007/s12206-015-1040-y>
- Klocke F, Beck T, Hoppe S, Krieg T, Müller N, Nöthe T, Raedt HW, Sweeney K (2002) Examples of fem application in manufacturing technology. *J Mater Process Technol* 120(1):450–457. [https://doi.org/10.1016/S0924-0136\(01\)01210-9](https://doi.org/10.1016/S0924-0136(01)01210-9)
- Bergs T, Röttger J, Barth S, Prinz S (2021) Approach to the numerical modelling of the chip temperatures in single grain scratching. *Production Engineering*. <https://doi.org/10.1007/s11740-021-01017-7>
- Carslaw HS, Jaeger JC (1959) *Conduction of heat in solids*. Oxford University Press, London
- Jaeger JC (1942) Moving sources of heat and the temperature of sliding contacts. *Proc R Soc N S W* 76:203–224
- DIN EN ISO 4287:2009-11 (2010) Geometrische Produktspezifikation (GPS) - Oberflächenbeschaffenheit: Tastschnittverfahren - Benennungen, Definitionen und Kenngrößen der Oberflächenbeschaffenheit. DIN Deutsches Institut für Normung e.V., Berlin
- Pala U (2020) Experimental investigation and modeling of diamond wire sawing of single-crystal silicon. Doctoral thesis, ETH Zürich. <https://doi.org/10.3929/ethz-b-000426867>
- Pala U, Süßmaier S, Kuster F, Wegener K (2018) Experimental investigation of tool wear in electroplated diamond wire sawing of silicon. *Procedia CIRP* 77:371–374. <https://doi.org/10.1016/j.procir.2018.09.038>
- Rowe W (2009) *Principles of modern grinding technology*. William Andrew
- Rowe WB, Morgan MN, Black SCE, Mills B (1996) A simplified approach to control of thermal damage in grinding. *CIRP Ann* 45(1):299–302. [https://doi.org/10.1016/S0007-8506\(07\)63067-4](https://doi.org/10.1016/S0007-8506(07)63067-4)
- Bhushan B (1987) Magnetic head-media interface temperatures: Part 1—analysis. *J Tribol* 109(2):243–251. <https://doi.org/10.1115/1.3261346>
- Yevtushenko AA, Ivanyk EG, Ukhanska OM (1997) Transient temperature of local moving areas of sliding contact. *Tribol Int* 30(3):209–214. [https://doi.org/10.1016/S0301-679X\(96\)00044-8](https://doi.org/10.1016/S0301-679X(96)00044-8)
- Tian X, Kennedy FE (1994) Maximum and average flash temperatures in sliding contacts. *J Tribol* 116(1):167–174. <https://doi.org/10.1115/1.2927035>
- Hull R (1999) *Properties of crystalline silicon*. INSPEC, London
- Miyoshi K (1998) *Structures and mechanical properties of natural and synthetic diamonds*. Report NASA Lewis Research Center, Cleveland, Ohio
- Behrens BA, Chugreev A, Bohne F, Lorenz R (2019) Approach for modelling the taylor-quinney coefficient of high strength steels. *Procedia Manufacturing* 29:464–471. <https://doi.org/10.1016/j.promfg.2019.02.163>
- Xiao HP, Wang HR, Yu N, Liang RG, Tong Z, Chen Z, Wang JH (2019) Evaluation of fixed abrasive diamond wire sawing induced subsurface damage of solar silicon wafers. *J Mater Process Technol* 273. ARTN 116267 <https://doi.org/10.1016/j.mssp.2020.105015>
- Wang L, Gao Y, Li X, Pu T, Yin Y (2020) Analytical prediction of subsurface microcrack damage depth in diamond wire sawing silicon crystal. *Mater Sci Semicond Process* 112:105015. <https://doi.org/10.1016/j.mssp.2020.105015>
- Li X, Gao Y, Yin Y, Wang L, Pu T (2020) Experiment and theoretical prediction for surface roughness of pv polycrystalline silicon wafer in electroplated diamond wire sawing. *J Manuf Process* 49:82–93. <https://doi.org/10.1016/j.jmapro.2019.11.022>

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