

KINEMATICAL AND MECHANICAL ASPECTS OF WAFER SLICING

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1. Definition of Variables

- a = Stroke length [mm]
b = Width of workpiece [mm]
C = Concentration of abrasive grains in lapping suspension [mm⁻³]
c = Maximum value of tool wear contour [mm]
d_k = Average grain diameter [mm]
e = Maximum value of vertical stroke [mm]
l_k = Length of contact zone between tool and workpiece [mm]
n_s = Stroke frequency [s⁻¹]
P_k = Average force per active grain [N]
p' = Specific blade load [N/mm]
r = Stroke ratio [-]
t = Cutting time [t]
v = Lapping or slicing speed [mm/s]
v_k = Velocity of contact point between tool and workpiece [mm/s]

2. Introduction

Slicing of silicon wafers by means of multiple-blade slurry sawing offers a great potential for increased productivity, as demonstrated in several analytical and practical investigations performed in the USA and Europe /1,2,3/. In order to realize the combined goals of higher productivity and reduced slicing cost, two main prerequisites have to be met first: the construction of a high-efficiency slurry-saw machine and the functional description of the technological fundamentals of this particular lapping process.

In the paper, some recently achieved results concerning the technological fundamentals of slurry sawing will be presented. First, a new concept of the specific material removal process and the related kinematic and geometric contact conditions between workpiece and saw blade are described. Based hereon, the result of a functional description of the slurry sawing process is presented, expressing the main process criteria, such as infeed per stroke, specific removal rate, specific tool wear, and vertical stroke intensity, in terms of the dominating process parameters, such as stroke length, width of workpiece, stroke frequency, specific cutting force and slurry specification.

The derived process models contribute to an improved understanding of the slurry sawing process, and provide a means for improved machine tool design and optimized selection of sawing conditions. This is demonstrated in the final part, comparing practical test results with the analytically derived process models.

3. New View on Material Removal in Slurry Sawing

Conventionally, the process of material removal in lapping is understood as a micro-chip formation process, where abrasive particles stick to the tool and are dragged over the work surface, thus removing material by ploughing, scratching and regular chip formation. Recent findings, however, show clearly that this kind of a real chip formation process never occurs really in a well controlled lapping operation. In the contrary, such an event results in an undesired scratch on the work surface, which is normally regarded as an indication for an inferior working result. The real material removal process in lapping is based on a rolling action of the abrasive particles in the gap between workpiece and lapping tool /4/. This is generated by the relative motion between tool and work surface and is supported by the lapping fluid, which forms a linear velocity field characterized by a constant degree of shearing. As a consequence, the abrasive grains do rotate even if they are not in contact with the tool and/or work surface, as demonstrated in Figure 1. As a result of this rolling action, the edges of the irregularly shaped

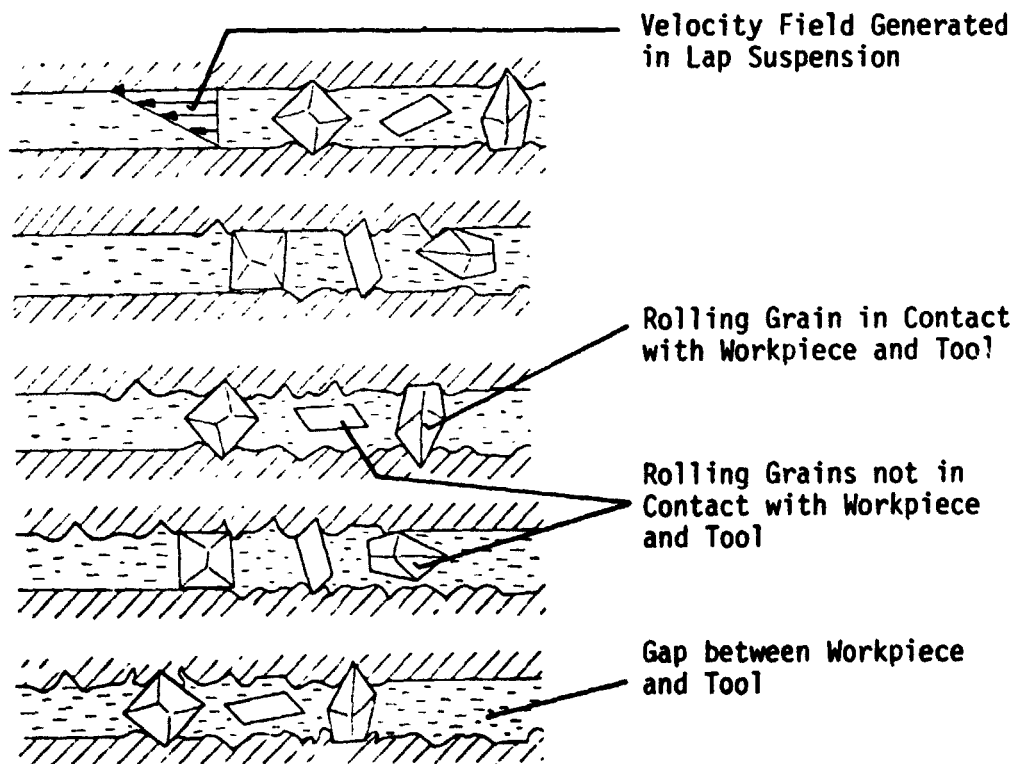


Fig. 1: Principle of grain rotation and material removal in lapping /4/

grains penetrate into the work surface at an extremely high rate. For example, a slurry with a concentration of $C = 10000 \text{ mm}^{-3}$, a lapping speed of $v = 500 \text{ mm/s}$ and a 30% grain participation factor results in 1.5 million impacts of grain edges per second and per square millimeter on the work surface.

In the case of ductile materials, like steel and superalloys, these impacts lead to a high degree of plastic deformation in the respective surface layer of the workpiece. As a consequence, the deformability of the material is reduced and the hardness is increased, both effects based on the principle of strain hardening. With ongoing impacts and deformations, the yield strength of the material is exceeded locally, and as a result small work particles of irregular geometry are separated from the work surface and removed out of the working area by the lapping fluid. With impact rates as high as demonstrated above, material removal rates in lapping can reach values comparable to precision grinding processes.

In case of rigid-hard materials, such as ceramics, carbides, and silicon, the micro-mechanics of the material removal process in lapping is even simpler. While the individual grains roll over the work surface with no tendency for plastic deformation at all, compressive stresses are induced into the work surface, which locally exceed the limits of strength of this particular material. As a consequence, flake-type of particles break loose from the work surface with no repetitive plastic deformation involved. Due to the rigid character of the penetration and separation process, the volume removed from the work surface by an individually impacting edge might be larger than the actual volume of penetration of the abrasive edge into the work material.

One specific characteristic of the lapping process is, that the tool is also subjected to the micro-impacts of the abrasive grains, and thus shows a certain loss, too. This tool wear can be reduced by selecting saw blades with favorable properties, such as high degree of elastic deformability, low strain hardening capability, and high yield strength.

In the case of slurry sawing of silicon material, the tool should have a sufficient capability for elastic/plastic reaction. Due to the rigid interaction between work material and abrasive grains, the impact forces need to be damped by means of an elastic/plastic interaction between grains and tool material. Otherwise, the reactive forces on the grain edges themselves would be too high, and would result in an excessive grain wear.

Utilizing this novel concept of material removal in lapping, it is possible to define the number of impacts N_r per unit of work surface and time by multiplying the concentration C with the lapping speed $v/3$:

$$N_r = K_1 \cdot C \cdot v \quad [\text{mm}^{-2} \cdot \text{s}^{-1}] \quad (1)$$

Assuming a quasi-proportional relation between the average force P_K per active grain and the amount of material removed per edge impact, the total amount of material removed per unit of work surface and per unit of time results to:

$$V_r = K_2 \cdot P_K \cdot N_r = K_3 \cdot P_K \cdot C \cdot v \quad [\text{mm}^3/\text{mm}^2/\text{s}] \quad (2)$$

In this function, which is used later for deriving the process model functions for slurry sawing, the proportionality factor K_3 is valid only for a given

combination of work material, tool material and abrasive material, as well as the particular specification of the lapping suspension used. Recent investigations show, that the volume of material removed per edge impact does, in reality, not increase exactly proportionally with the average load per grain, but rather shows a slightly degressive increase. The implications of this non-linear behavior are of secondary importance and will not be taken into further consideration in the context of this paper.

4. Kinematic and Geometric Conditions of Contact between Workpiece and Blade

Figure 2 represents the basic geometric and kinematic conditions of the slurry sawing process. The individual saw blade is moved back and forth with the varying speed $v = f(x)$, the stroke length a , and the stroke frequency n_s , cutting into a block of work material with the width b . As a result of the varying cutting speed, the resulting blade wear is uneven versus the length of contact. At point A (upper part of Figure 2), the slicing speed v is at its maximum ($v = v_{max}$) and so is the blade wear. At point A'' (lower part of Figure 2), the maximum stroke position is reached and the related slicing speed becomes zero ($v = v_{min} = 0$), and in accordance with this the blade wear is zero, too. As a result, a quasi-elliptic wear profile is formed in the tool. This geometric deviation from the original straight tool profile bears dramatic consequences for the whole process, as a similar curved profile is generated in the work surface, exposing a stronger curvature versus its entire extension than the tool profile. Actually the two mating profiles are congruent, because they are bound to have identical tangents in their respective points of contact.

Most important for the understanding of the slurry sawing technique, and in strong contrast to the conventional concepts, is that tool and workpiece actually have a point contact rather than a line contact versus the total work width as formerly assumed.

There are two other specific characteristics of the slurry sawing process, which can be derived from Figure 2. The first one is related to the fact, that the contact point (A, A', A'') moves with the speed v_k opposite to the actual motion of the blade indicated by the blade speed v . The second characteristic refers to the vertical motion the blade is forced to make, while the blade contour works its way up on the contour of the workpiece. This vertical stroke is indicated by the vertical blade speed v_e and represented by the maximum vertical stroke length e valid for the extreme positions of the saw blade. In essence, the vertical stroke phenomenon is the reason for the dynamic instability of the slurry sawing process and causes major process disturbances especially at high stroke rates and cutting speeds. As a consequence, measures to compensate or minimize this effect are essential for high-efficiency slurry sawing processes.

From Figure 2 the following functions concerning the basic geometric and kinematic relations of slurry sawing can be derived:

a) Maximum vertical stroke e :

$$e = c \cdot \frac{a}{a+b} \quad [\text{mm}] \quad (3)$$

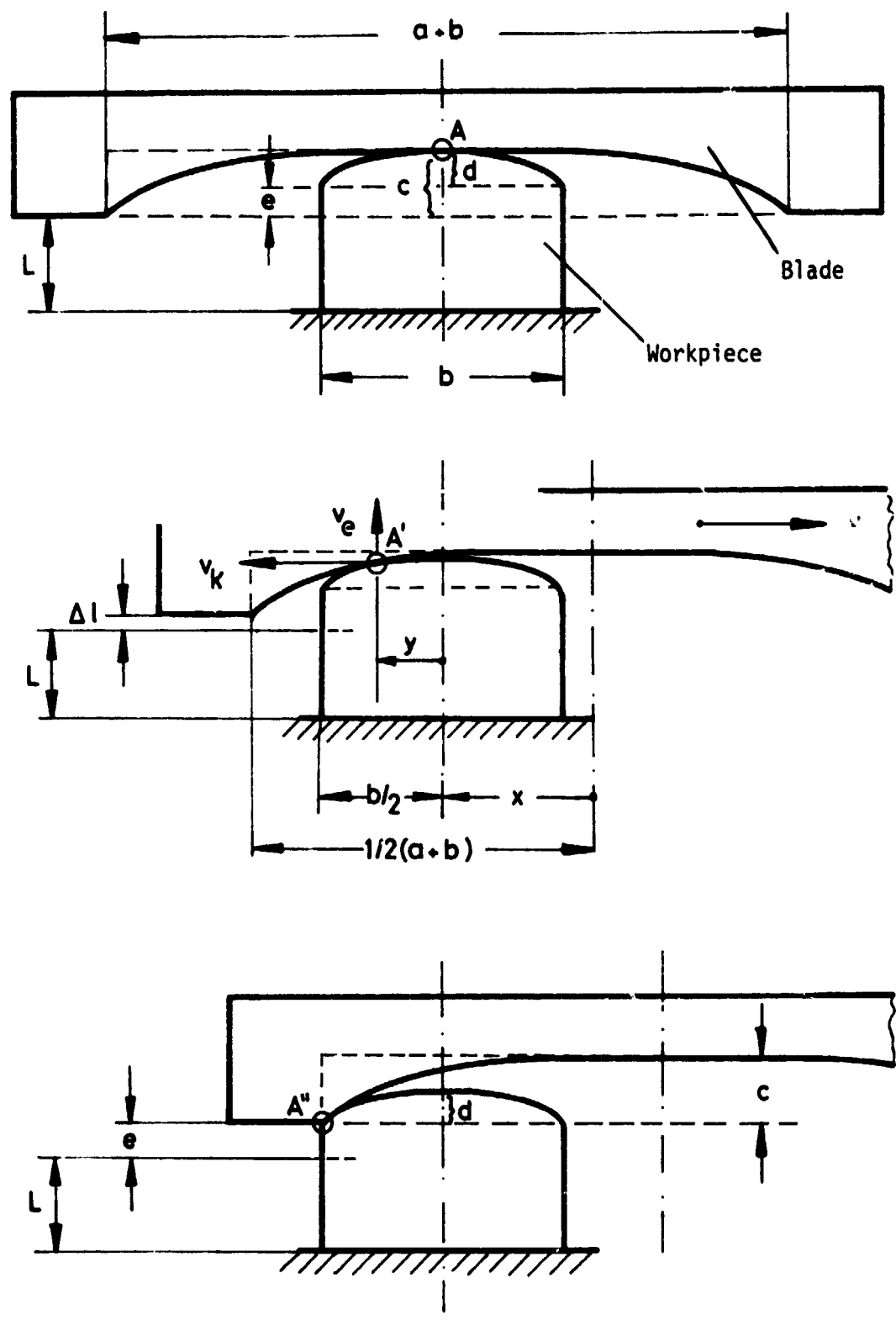


Fig. 2: Representation of geometric and kinematic conditions of the slurry sawing process /3/

b) Velocity of contact point v_K as a function of the simultaneous cutting speed v :

$$v_K = v \cdot \frac{a}{b} \quad [\text{m/s}] \quad (4)$$

c) Ratio between maximum blade wear c and maximum workpiece contour d :

$$\frac{c}{d} = \frac{a+b}{b} \quad [-] \quad (5)$$

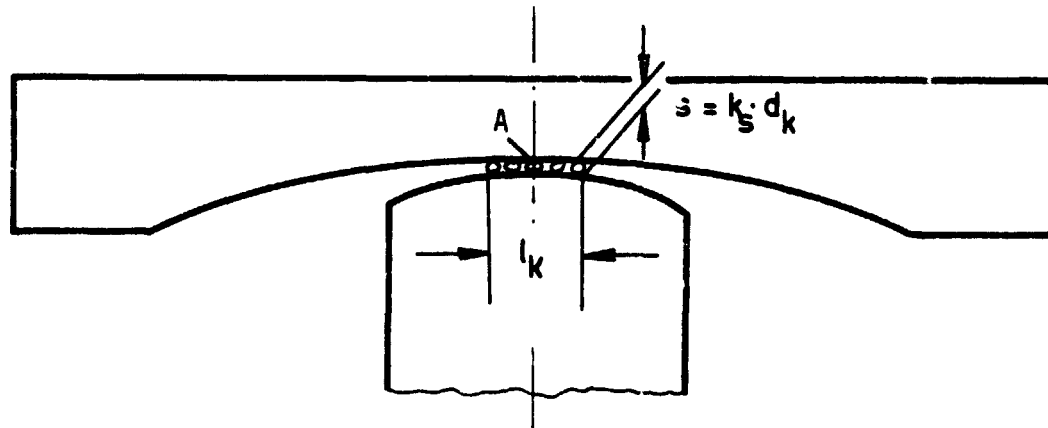


Fig. 3: Actual contact conditions between workpiece and saw blade

The actual contact conditions between workpiece and blade are such that active grains are distributed around the theoretical point of contact A covering a confined width of contact l_K (Figure 3). Based on certain assumptions regarding the grain distribution and the average depth of penetration of cutting edges into the tool and work material /3/, the contact time t_K for which any point of the work surface is subjected to the lapping action results to:

$$t_K = \frac{l_K}{v_K} = \frac{l_K}{v} \cdot \frac{a}{b} \quad [\text{s}] \quad (6)$$

Further analytical investigations have been carried out to describe the actual width of the contact zone l_K , revealing that it is a complex function of the average grain diameter d_K , the cutting force P' per unit of blade width, the stroke frequency n_s , the cutting time t , the stroke length a , and the width of the workpiece b . This, however, will not be dealt with here, as l_K is cancelled out in the course of the analytical derivation of the process models, based on the grounds of the already mentioned linear relationship between average force per grain and average material removed per edge impact /3/.

5. Functional Description of Process Criteria

Based on the geometrical and kinematical fundamentals of the slurry sawing process described above in brief, the following functions related to the main operational process criteria have been derived in a recently finished study /3/:

a) Depth of cut per stroke of saw blade:

$$f_e = K_f \cdot \frac{P'}{d_K^\alpha} \cdot \frac{a}{b} \quad [\text{mm}] \quad (7)$$

b) Feed rate:

$$f = f_e \cdot n_s = K_f \cdot \frac{P'}{d_K^\alpha} \cdot \frac{a}{b} \cdot n_s \quad [\text{mm/s}] \quad (8)$$

c) Specific removal rate:

$$Z' = K_f \cdot \frac{P'}{d_K^\alpha} \cdot a \cdot n_s \quad [\text{mm}^2/\text{s}] \quad (9)$$

d) Maximum blade wear:

$$c = K_v \cdot \frac{P'}{d_K^\beta} \cdot n_s \cdot t \quad [\text{mm}] \quad (10)$$

e) Ratio between material removal and blade wear ($r = a/b$):

$$G = K_g \cdot d_K^{\alpha-\beta} \cdot \frac{r}{r+1} \quad [\text{mm}^3/\text{mm}^3] \quad (11)$$

f) Maximum vertical stroke:

$$e = K_v \cdot \frac{P'}{d_K^\beta} \cdot n_s \cdot t \cdot \frac{r}{r+1} \quad [\text{mm}] \quad (12)$$

The feed rate f and the specific removal rate Z' show a proportional increase versus specific cutting force $P' = P/b_s$ (P = total force load per blade, b_s = width of blade), stroke length a and stroke frequency n_s . The influence of the average grain diameter d_K on these two process criteria is not clearly decided and depends on the actual positive or negative value of the respective exponent α . On the other hand, the grain concentration C of the lapping suspension does not appear to have an influence on these and the other process criteria in the context of the presented analysis. This result is again based on the assumed linear relationship between average force per grit and average material removed per individual edge impact. However, practical tests indicate, that there is indeed an optimum grain concentration for given operational process conditions. As a consequence, this specific relation will be checked further, including the application of a non-linear relationship to describe the material removed per individual edge.

Another result is more obvious, proving that the specific removal rate Z' is independent from the effective width b of the work piece. This actually means, that for a given set of cutting conditions, the volume cut per unit of time is always the same, independent from the actual width of the workpiece.

Similar structures as derived for feed rates and removal rates have been obtained for the process models concerning the wear related process criteria such as maximum blade wear c , abrasive ratio G , and the maximum vertical stroke e . The last two criteria show a strong dependency of the stroke ratio

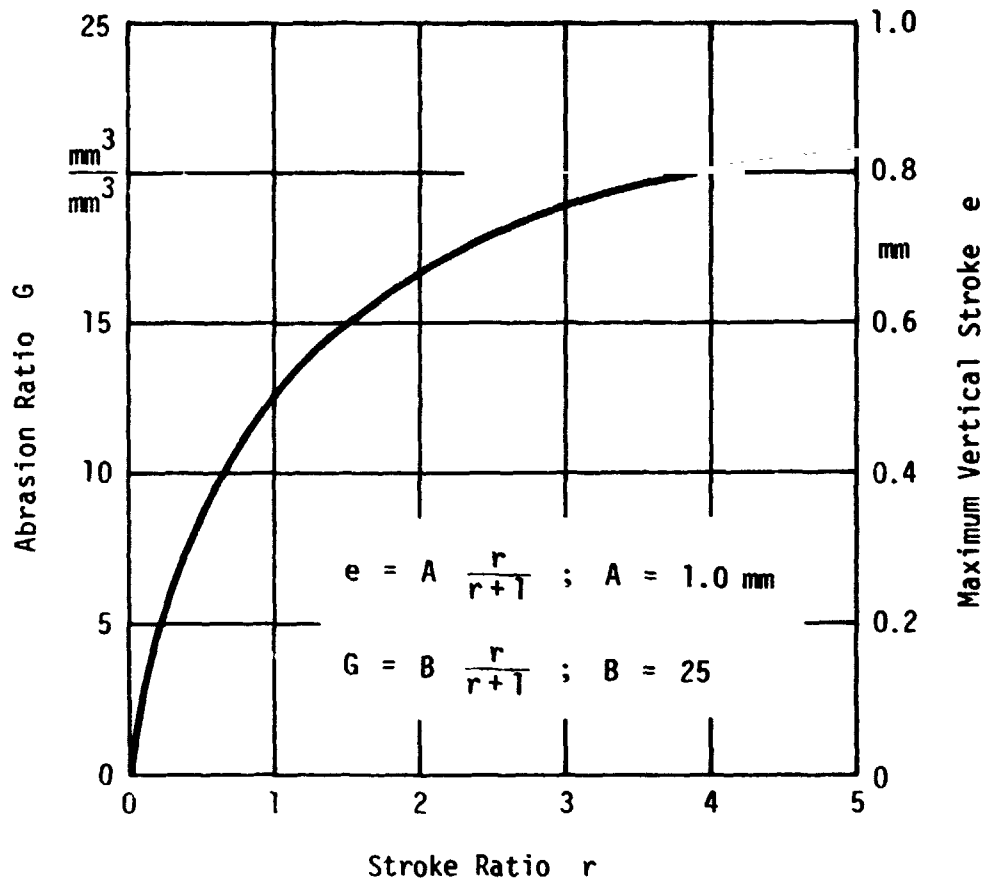


Fig. 4: Qualitative representation of abrasion ratio and vertical stroke versus stroke rate

$r = a/b$ ($a =$ stroke length, $b =$ width of workpiece). The respective functions are displayed qualitatively in Figure 4, showing that the G -ratio improves degressively with increasing stroke ratio r . As a result, tooling cost are decreased, and productivity in form of increased removal rates could be improved, too. On the other hand, however, the disturbing vertical stroke e is increased at the same rate versus r , indicating that counteractive measures to reduce the intensity of e is an important requirement in case of higher stroke ratios. The same is true for higher stroke rates n_s , as the vertical stroke intensity increase proportionally with n_s . The abrasive ratio G , on the other hand, is independent from n_s , because both, the removal rate and the wear rate increase at the same rate versus n_s , and thus this influence is cancelled out.

6. Comparison between Analytical Results and Practical Tests

Slicing test performed in the USA reveal a promizing accordance of the derived process model functions with the test results /1/. In Figures 5 to 8 recorded abrasion rates and cutting rates, which are in fact identical with the specific removal rate Z' defined above in equation (9), are plotted ver-

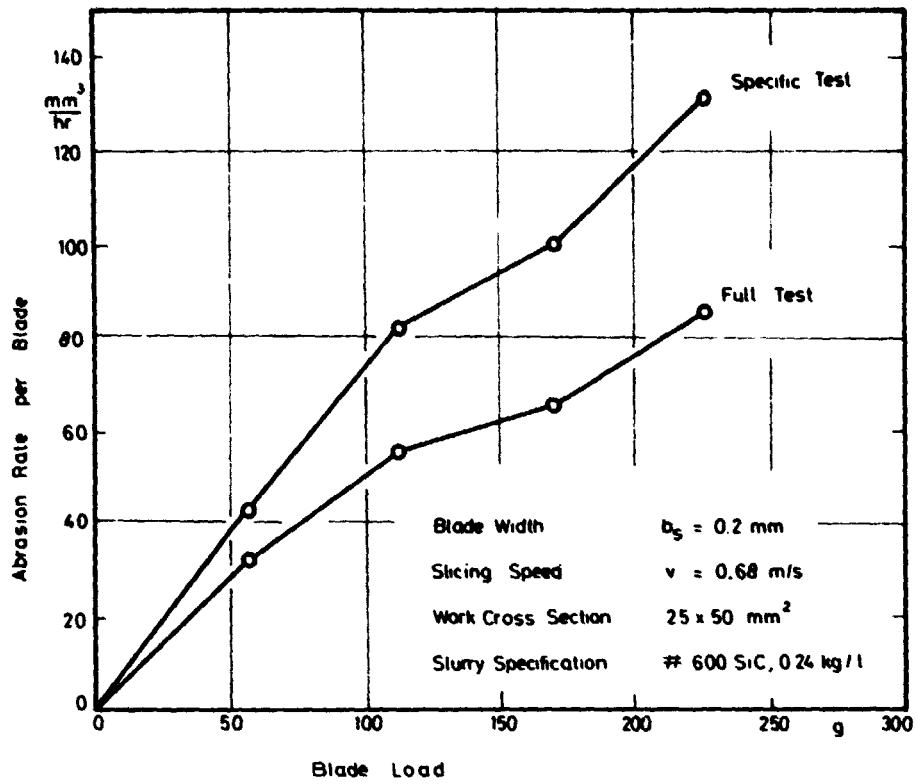


Fig. 5: Abrasion rate per blade versus blade load in slurry sawing /1/

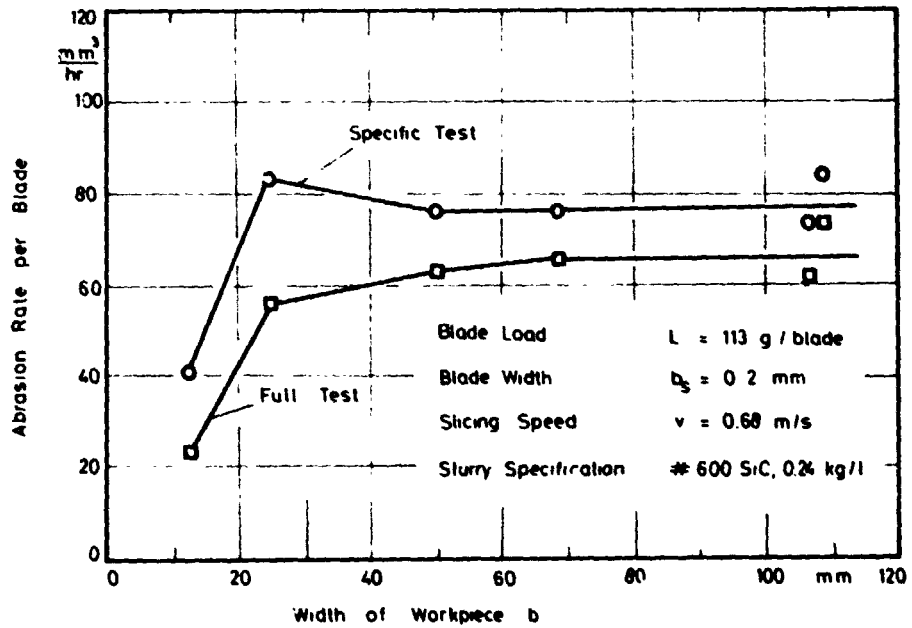


Fig. 6: Abrasion rate per blade versus width of workpiece in slurry sawing /1/

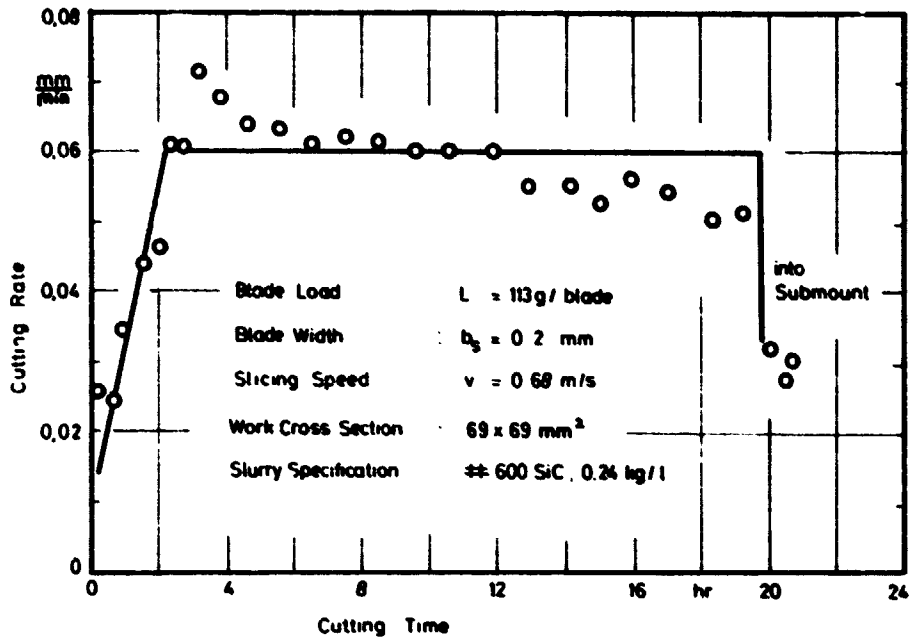


Fig. 7: Cutting rate versus cutting time in slurry sawing /1/

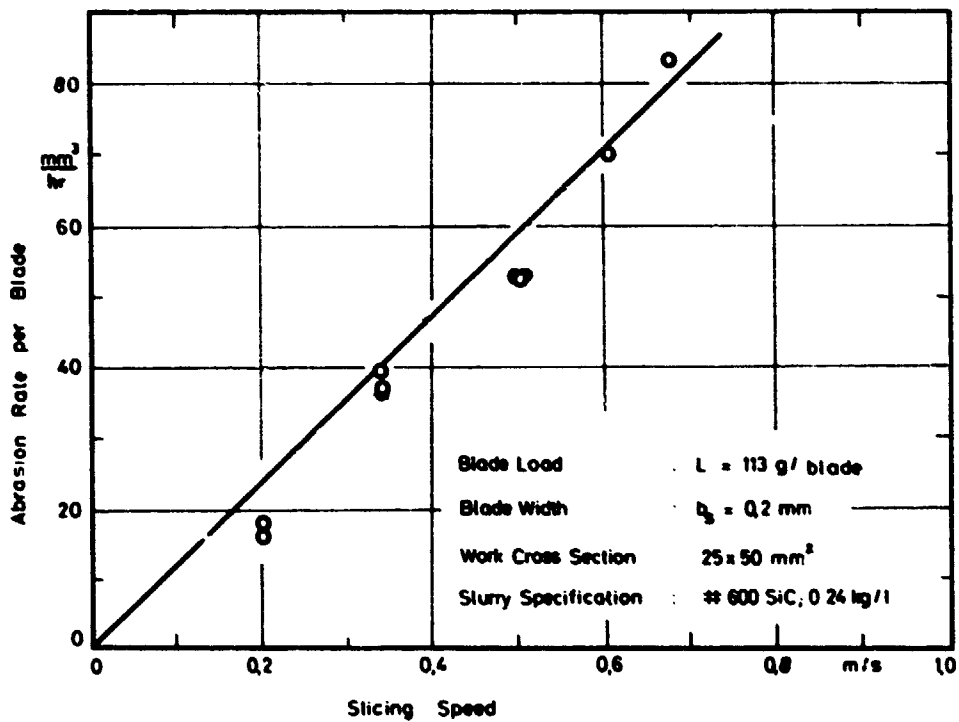


Fig. 8: Abrasion rate per blade versus slicing speed in slurry sawing /1/

sus various process parameters. Figure 5 shows clearly the almost proportional increase of the material removal rate versus the blade load, while in Figure 6 the independence of the removal rate from the width of the workpiece is demonstrated. Only at a small width of less than $b = 20$ mm, the recorded removal rates drop, most probably because of an improper generation of the work contour. The quasi-constant removal rate versus cutting time becomes evident from Figure 7. In the beginning of the slicing process, the removal rates are lower due to the fact that the proper contours of tool and workpiece are not established yet. With increasing cutting time, however, the mating contours develop gradually, and at the same time the removal rates increase until the optimum, steady-state of operation is reached. In the tests cited, a slight decrease of the removal rate was observed at steady-state conditions instead of the expected constant behavior. Further investigations of the slurry sawing process, which will be carried out as part of a major practical research program, are scheduled to decide whether this declining tendency is a general characteristic of the process based on geometrical and/or mechanical deviations, such as tool wear and work contour changes, or whether the observed behavior occurred on the grounds of an unidentified disturbance. Finally, a very clear tendency is demonstrated in Figure 8, proving the exactly proportional increase of the removal rate versus the slicing speed, which on the other hand is identical with an increasing stroke rate a at a constant stroke length b .

7. References

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DISCUSSION:

SCHMID: Your model is very interesting. When I first got into this, I was using the slurry saw and was using blades with fixed diamond on the bottom. And, in fact, it would not cut. If it had any kerf length at all, it would not cut. What I did was to make a step-block, which was a 1/4-inch, 1/2-inch, 3/4-inch--varying kerf lengths, to see how effectively it would cut for those particular kerf lengths, and it cut fairly well in the 1/4 inch. Once I hit the half-inch, it almost stopped dead--this was with sapphire--and from that I came to the idea of rocking. I could never really understand why there was a significant difference between cutting with a diamond, the fixed abrasive, as opposed to the loose abrasive, and I think your model explains that very nicely.

WERNER: Yes, it exactly explains it. If you have some kind of line contact, your removal rate is very low. The main reason is that the contact between work and tool is too long, and so the distribution of the load over many thousands of grits results in a too small load per grit and nothing happens. Only if the contour is such that your real contact lengths between the tool and the workpiece is small enough, does the process work.

SCHMID: It might be interesting to try a step-block. I did this with sapphire, and saw, in fact, the 1/4-inch, I was able to physically cut with it. There was movement. It would be very interesting to try the same kind of experiment with silicon to see what, in fact, is that contact length for the particular load that you're using.

WERNER: You could increase your load, theoretically. But as it begins to buckle, you never get to that high total load. But the load per grit is high enough for cutting action to start.

JACKSEN: Considering, with slurry saws, the problem of this buckling process, how would you feel about raising pressure to increase cutting rates? Consider that the contact area's being so small would result in dramatically increased kerf sizes as the parts started to get either some vibration or some extra motion in the non-desired edge. That is, is there some point in tension, which would be optimum considering the 80% elongation?

WERNER: There is an optimum relation between the stroke lengths and the work widths. That is roughly in the vicinity of 1:1. That means that stroke lengths and work widths should be the same. Now, about the contour in your blade, the work contour is just twice as long as the work width is. If you would increase the stroke length, which has some advantages, then you would weaken your blade with respect to the danger of buckling. And, therefore, you would rather reduce the stroke length and have also a smaller blade length, and increase--instead of that--the stroke frequency. So it helps very much to speed up the process, if you can increase the load. It helps also to increase the stroke length. It helps to increase the frequency. But there are constraints that are given by the system and by the machine. And that is exactly what we are now dealing with to find the optimum conditions of these partly contradicting influences of the process parameters. There is some kind of optimum set of working conditions. For that we need a better machine.

QUESTION: What do you feel the optimum speed of sawing could be from this system if you optimized it?

WERNER: Actually, the answer is as fast as possible. I would like to have a machine that can go up to 200 meters per minute, maximum speed. You see the speed goes from a maximum value to a minimum one.

QUESTION: You're talking about speed of reciprocation, or speed of sawing? I didn't understand.

WERNER: Speed of sawing and the in-feed velocity. I think it is possible, one day, to arrive at such speeds that you can cut through a 10-x-10-centimeter, or 4-x-4-inch, ingot in less than an hour.

QUESTION: They are doing that now with diamonds, sawing ID, are they not?

WERNER: Yes, but one wafer after another. Here you have the same speed for 300 wafers at the same time, so that results in less than 10 seconds per wafer.

QUESTION: But you also have a changing parameter in this system. That is, your blade is changing shape as you're sawing. Does not that variable give you a headache in the single-point forces that you're talking about?

WERNER: Not in the shape itself, but in the accumulation of the compounding forces at the end. You come to a point, especially if you have long strokes, where you have a disadvantageous kind of wear profile. You have a wear profile that is straight and then suddenly breaks off. So you have a very strong component force at the end. If you have smaller strokes, and faster ones, then your wear profile is more smooth, and you don't experience this problem so much. However, in time, these disturbing forces grow, and you come to an end where you can no longer continue to use your blade system. The best is just to use one blade for one cut, and then throw it away and put another set of blades in.

QUESTION: The shorter the stroke, the worse the problem is with the removal of the slurry, and with heat buildup.

WERNER: That's clear. Because if you reduce your stroke lengths to zero, what do you have? Nothing. Actually, your contact point--let's say you have 1- or 2-millimeter stroke length--then your point of contact is switching, going from one side of the workpiece to the next at the stroke rate; however, the real rolling action, because of the small relative motion between work and tool, is very very small, and it approaches a zero removal rate.

HEIT: There was reference made to an enrichment in the concentration of the slurry as it passed into the work area, the specific pressure section. You mentioned that it almost doubled from 10,000 grains per cubic centimeter to 20,000 grains per cubic centimeter. Is there any speculation at this point as to why that is happening in the slurry? We have slurries that are used in fuel treatment, which behave somewhat along those lines, when they have to be forced through narrow apertures. There's a distortion in their weight percent.

WERNER: You see here the speed of the centerpoint of my grain is half. So it is in tune with the speed of the liquid, while here, that point of the cutting edge, has exactly the speed of the workpiece and so does the speed of the outmost layer of the liquid. Here that point of the particle has a speed of zero because it sticks into the workpiece, and so does the liquid in contact with the workpiece. Now, you see that results in the fact that average speed of the particles is half of the speed of my lapping tool. But the concentration in the gap is twice the concentration of the particles in the free suspension. Just because they are forced to go through this gap, which is roughly the average size of the grain diameter. Because, in a free distribution, you never have them all aligned in one little gap and line, but rather, if I had a model of the free suspension here, I would have a concentration that could be put into a gap double as big as this gap, but the same number of grains, actually. Forcing a liquid with solid particles into a small gap, nearly as small as the diameter of grit itself, results in a condensation and an increase of the concentration of the grit in the fluid.

WOLF: Does that mean speeding up the fluid velocity?

WERNER: You are right. Actually, the fluid that was here may that result in a compression of the fluid. But I think we have to find out what the answer is here. But we have grains in the gap, I'm sure, and you have also the lapping component, because that is not only necessary for getting the particles in rotation, but also for getting the debris out. If you did not have a liquid vehicle here, we never could get the silicon particles out of this gap and it would clog pretty fast.

MORRISON: I wonder what the practicality of continuous or periodic blade dressing would be to overcome the problem of stroke shortening for excessive blade wear. People shorten the stroke, and therefore shorten the bladeflife, when the rounding wear becomes excessive. Is blade dressing one alternative to stroke shortening?

WERNER: Blade dressing to remove contamination. But changing the curvature is a problem because there is such a delicate equilibrium between the working conditions and the right profile, that any dressing process would disturb this equilibrium and would result in a reduction of the removal rate. But it is an interesting point to think about blades with fixed abrasive having the right contour. Of course, that is such a natural view to put on this problem, we are trying that and it seems to work very well. If we start with a straight blade with diamond particles, we have a rather slow process, especially if the workpiece develops a straight flat contour too. It comes to an end and we cannot just put the pressure on. It's like a sawing process with a very wide workpiece. However, if we just have a little concave contour on the tool, it works very good.

BOSOMWORTH: You started your talk with a comment that you thought that shortly there would emerge some techniques that came close to meeting the solar cell goals. I'd like to invite you to comment further on that ... you've certainly gone through some fundamental things here that would speed up multi-wire cutting. Are we, in your opinion, going to see some machines in the near future that are greatly improved, and where are they going to come from?

WERNER: I'm sure that we'll see some machines emerging both in the multiple blade slurry area and also with wires.

JACKSEN: How about the silicon carbide particles breaking down and perhaps causing your cutting rate to decrease, because the particle sizes are starting to get smaller? I ask that in the context not only of silicon but of fused silica, which is my main interest.

WERNER: We did not experience that over a period of 30 hours. Over this time, there was no deterioration visible with regard to the average shape and size of the silicon carbide grains. If we see that, over a time, constant stroke lengths bear problems, we could think about reducing gradually the stroke length by 2% or 3% and avoiding the pounding effect at the very end of the stroke. However, there's no machine available on the market at the moment, where you could gradually reduce stroke lengths in process.

LYNAH: Our machine has infinitely variable stroke lengths. We can program it-- it's not normally done, but it can be programmed to change the stroke length as it is sawing.

LANE: You have told us it appears that the process works best with the curvature. Are you saying that if we could magically make a machine that has perfectly flat blades and maintains them, that we'd have slow cutting? Is it a force problem?

WERNER: If you want to have a straight tool, you can rock the workpiece and then you have this difference in curvature, and by that, a point contact. It is, basically, an inherent characteristic of the process, which of course depends on the force of the millions of impacts of the grains on the tool and the workpiece. And then, it stretches in the blade over a greater length, and this length is the width of the workpiece plus the stroke length, while the contour in the workpiece is just confined to the width of the workpiece. So you are bound to have a smaller curvature in the tool, and a contour with a larger curvature in the workpiece.

LANE: The problem I have in understanding this is that in wire sawing the wire bends. We have conformity and contact through a very long arc, and that still cuts.

WERNER: Yes. It cuts because of the high speed. And it's not a rolling process, nor a scratching process. And if you would look into how many diamonds on a wire really cut, you would be amazed how small this number is. Actually, the slurry wire saw system can only improve from these relatively low cutting rates. If the angle of contact between the workpiece and the wire is larger--that means go round 180 degrees--and pull it down, then you can increase cutting width. I don't know whether somebody is trying that, but it requires a different kind of machine too. First you have to have an idea, and understanding of the process, and then you have to try to do it. But what was done over the past few years, was just try something without an idea. And that was the reason why the progress was small. Maybe I'm biased because I'm working in this area. I favor the multiblade slurry technique because with regard to the difficulties related to the machine, to the tool, and all that, it seems to be the least compilation of problems. But with wires, you have a lot of other difficulties. Wire

is very small, it can break, you have to guide the wire, and as it goes out of contact, it takes slurry with it. You see, if you can achieve a better result with a slurry saw, then I think at least the people involved in this business would forget the wire saw. On the other side I am very much interested in following up progress on these wire saws.

In the ID sawing process, if the workpiece does not rotate, of course, you have a line contact over the total contact length, the total width of the workpiece. And for the kind of heavy total load, between the tool and workpiece, you need bonded abrasives and you need a very rigid cutting edge. That's the main reason why it is done internally. OD sawing would not be possible, at least not easily, by that method, because the total contact forces between the blade and the workpiece are too high and such a thin saw blade would buckle.

WALLITT: What if you rocked the work while you were doing it?

WERNER: You see, I have to point in one direction always. And the big advantage of a slurry saw is that you can indeed cut up to 300 or more wafers at the same time. So even if the cutting time, for one cutting process, is an hour or two, the resulting average cutting time for an individual wafer is a few seconds. 10-15 seconds. It's very difficult, at least if you go to a larger cross section of your ingots, to achieve that, as we heard yesterday, with an ID saw. However, I want to make another statement. The ID sawing system, especially if it is further improved, is a very good cushion to rest on as long as other techniques are not available or fail. And I am pretty sure that if a high-efficiency slurry technique were to come through, the ID sawing and tool manufacturers would not sit back and just give up. I think then some of the possibilities they have to further increase their removal rates and decrease the cutting cost would be tried out. You can see the same kind of competition between processes in other fields too. And very seldom is one process completely wiped out when another one comes up that does a little better.

SCHMID: A little while ago you made a comment that when you're rocking with fixed-diamond abrasive, the number of particles that actually are in contact with the work is very small, far smaller than you would expect. This is something that we are trying to achieve, to minimize the actual contact point, so we can achieve high pressure at the diamond tip. What makes you feel that number of contact points is minimal?

WERNER: A shadowing effect. You see, if you have a saw blade, let's take a bandsaw where theoretically the blade goes down vertically and you have cutting edges all aligned at the same line, theoretically only one can cut. So you need a certain distribution of cutting edges in a small field. In a normal bandsaw operation, not more than a tenth, or even less of the teeth, really cut. That goes on until the one that protrudes most is worn away, and then that which follows next, at a certain position, takes over the cutting. That is true for grinding too. Especially in this plunge ID process. It is possible that on the whole circumferential area of the wheel, from the many thousand grits only a few hundred are, at a certain point of time, really cutting. And that explains why the tool life is so high, in my view. So the number of engaged edges in grinding, and I dealt with that problem in conventional grinding very much, is much smaller than you think. With the wire sawing process, where you have this problem of

getting enough normal force on your edges, one way out is to have fewer of them really working, and taking the load off a certain length of the wire.

SCHMID: Yes. Rocking it. And the other thing, of course, is that by going to a finer particle size, we saw a much more effective cutting action. By going to a finer particle size, the number of contact points is going to be increased substantially.

WERNER: It always helps to know how many edges in a microchip formation type of process are in real contact with the workpiece. In most of these processes it is very unclear. We have very little means of calculating or measuring the real number engaged. If you understand the process well, that understanding might also force you to give up.

SCHMID: Yes. The other thing that you can do to minimize your number of points in contact to increase the pressure is in fact to have a larger rocking angle, which will minimize the curve.

WERNER: Yes. The end cutting speed helps also. You can, to a certain extent, overcompensate this deficiency of low forces by a higher speed.