Abstract
European Photovoltaic Solar Energy Conference and Exhibition
Hamburg, Germany
September 21-25 2009

Subject number: 2.1

Full title: Fluid Mechanics of Wire Sawing

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Purpose of the work

The goal of this investigation was to examine the fluid mechanical phenomena associated with wire sawing.

Approach

Because wire sawing involves high-speed phenomena (wires are drawn at 5 – 20 m/s) in a microscopic gap (tens to hundreds of microns) filled with an opaque slurry (abrasive micro-particles in a liquid carrier), it is difficult to perform any direct fluid mechanical measurements and observations.

Using similarity principles, it is possible to scale-up the experiment by a factor of 10 or more, and thus conduct investigations with wires, particles, and gaps in the millimeter-size range. A physical phenomenon can generally be described by a number of dimensional parameters, and the use of the well-known Pi-Buckingham theorem allows the physical parameter space to be replaced by a space of dimension*less* parameters. If such dimensionless parameters are preserved when going from the real setup to the scaled-up setup, then all physical phenomena can be guaranteed to be authentically reproduced.

Scientific innovation and relevance

The dimensionless parameter space was thus divided among two innovative laboratory experiments: a rigidly *rotating wheel* and an actual *sliding wire*.

The rotating wheel allowed investigations of the particle dynamics in the high-shear flow region between the “wire”, embodied by a high-speed rotating disk, and the “wafer”, consisting of a groove in a transparent pad that was set at an adjustable distance from the disk rim. The peripheral speed of the wheel could reach speeds up to 5 m/s while sliding in a groove of 4 to 6 mm in width. The “slurry” consisted of a base liquid (water or mineral oil) and “abrasive” particles of appropriate size (glass or polystyrene spheres and sand crystals ranging from 100 microns to 1millimeter). The main drawback of this setup was the constant value of the gap size, which was pre-determined.

In order to better understand the dynamics of the gap size on the cutting process, a scaled-up version (20x) of the actual wire-saw has also been assembled. A plexyglass groove of 4 mm to 6 mm in width and 1 meter in length was used to emulate the wafer cutting zone. Wires were made of thermo-weldable polyurethane round belts (4 mm in diameter) of varying hardness (85 Shore A to 100 Shore A). Wire speeds ranging from 1mm/s to a few cm/s were tested. The same slurry as in the wheel setup was injected in the groove. Care was taken to preserve the similarity parameters between the actual wire-saw and our model system. However, unlike the rotating wheel, phenomena associated with the (violent) cutting process were not faithfully reproduced in the sliding wire setup.

Results

The following observations were made.

1. The wire-ingot gap is NOT the result of lubrication. A lubrication model that takes into account lubricant side loss yields gap sizes that are smaller than the particle size themselves. Previous theories have omitted the important phenomenon of lubricant loss in their analysis and have reached the incorrect conclusion that wire-ingot gap is larger than particle size.
2. The wire-ingot gap is determined by the largest particle size present in the gap, the stacking of smaller particles on top of each other, and the distribution of particles under the wire along the whole length of the wafer.
3. Large abrasive particles that are pressed down by the wire tend to be ejected from the base of the cutting zone and migrate toward the lateral zones, in between the wire and the wafer surface. Smaller particles are spread over the whole cutting zone without any particular affinity for the cutting regions (base or lateral).
4. The particle-free flow between the wire and base of the groove is not a standard Couette flow (linear profile), but can be better represented by the flow induced by a sliding cylinder (wire) placed eccentrically inside a larger cylinder (groove). Particles within the gap strongly alter the basic flow.

Conclusion

We have discovered some novel phenomena in the fluid mechanics of wire sawing, which may enable the development of new technologies aimed at cutting wafers of smaller thickness and better surface quality.

Explanatory pages (2) for: Fluid Mechanics of Wire-Sawing

Multi-wire sawing is the main slicing technique for large multi- and monocrystalline silicon crystals in the photovoltaic and microelectronic industry (Möller H.J. 2006 “Wafering of silicon crystals,” Phys. Stat. Sol. (a) **203**, No. 4, 659–669).

Because wire sawing involves high-speed phenomena (wires are drawn at 5 – 20 m/s) in a microscopic gap (tens to hundreds of microns) filled with an opaque slurry (abrasive micro-particles in a liquid carrier), it is difficult to perform any direct fluid mechanical measurements and observations.

Using similarity, it is possible to scale-up the experiment by a factor of 10 or more, and thus conduct investigations with wires, particles, and gaps in the millimeter-size range.

A physical phenomenon can generally be described by a number of dimensional parameters, and the use of a known theorem (the Pi-Buckingham theorem) allows the physical parameter space to be replaced by a space of dimensionless parameters. If such dimensionless parameters are preserved when going from the physical setup to the laboratory setup, then all physical phenomena can be guaranteed to be authentically reproduced.

I. Scaled-up wire facilities

Because the number of parameters that fully describe an actual wire-saw is relatively large, it is generally not possible to build a *single* scaled-up facility that reproduces *all* phenomena at once (equivalently, not all dimensionless parameters can be kept constant while going from the wire-saw to the laboratory experiment).

The dimensionless parameter space was thus divided among two distinct laboratory experiments: a rigidly rotating wheel and an actual sliding wire. The rotating wheel (which acts like a disk-saw) allowed the investigation of phenomena associated with high slurry velocity while maintaining substantial abrasive (normal) forces. The drawback was that the gap size was pre-determined and fairly constant. The sliding-wire setup was better suited for the analysis of gap size. However, phenomena associated with the (violent) cutting process were not faithfully reproduced in the sliding wire setup.

1. The rotating wheel

Our laboratory has been performing investigations of the particle dynamics in the high-shear flow region between the “wire”, embodied by a high-speed rotating disk (Figure 1), and the “wafer”, which was represented by a groove in a transparent pad that was applied at an adjustable distance from the disk rim. The peripheral speed of the wheel could reach speeds up to 5 m/s while sliding in a groove of 4 to 6 mm in width. The “slurry” consisted of a base liquid (water or mineral oil) and “abrasive” particles of appropriate size (glass or polystyrene spheres and sand crystals ranging from 100 microns to 1millimeter).

Figure 1: A rotating wheel (left) was designed with appropriate edge geometry in order to emulate the sliding wire geometry. A thermo-formed plexiglass groove (right) of appropriate width was applied against the disk edge and slurry was injected into the disk-groove gap.

2. The sliding wire

In order to better understand the dynamics of the wire on the cutting process, a scaled-up version (20x) of the actual wire-saw has also been assembled (Figure 2). A plexyglass groove of 4 mm to 6 mm in width and 1 meter in length was used to emulate the wafer cutting zone. Wires were made of thermo-weldable polyurethane round belts (4 mm in diameter) of varying hardness (85 Shore A to 100 Shore A). Wire speeds ranging from 1mm/s to a few cm/s

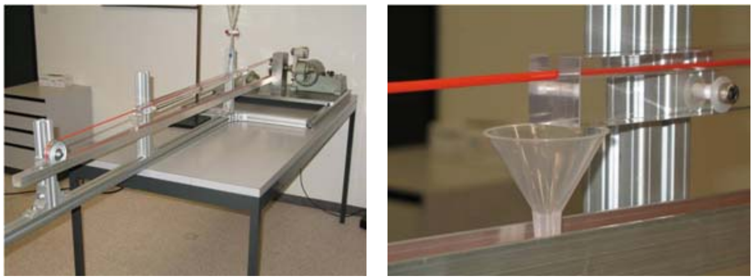

Figure 2: The scaled-up version of the wire-saw consisted of a round belt driven by a motor through a plexyglass groove (left). The belt tension could be adjusted by varying the idler pulley position, while the wire normal pressure against the groove base could be adjusted by varying the “wafer” position with respect to the wire (right).

were tested. The same slurry as in the wheel setup was injected in the groove. Care was taken to preserve the similarity parameters between the actual wire-saw and our model system.

II. Observations

In the rotating wheel setup, a few characteristic phenomena that were observed were *particle jumps* and *particle side migration.*

As the "wire" (disk) presses onto the particles, they tend to be pushed towards the sides of the groove. Since the larger particles are the ones that are in direct contact with wire and ingot, they are the ones that probably contribute the most to the side cutting and are responsible for the wafer final surface quality. Smaller particles most likely remain at the bottom of the groove and act as "fine-grit sand paper".

Another most peculiar phenomenon occurred in this setup: as the disk pressed onto the particles, they "jumped" with extremely high speed (meters per second) towards the side of the groove. These jumping events are probably closely related to the tendency of the larger particles to migrate toward the sides of the groove.

The wire setup placed under scrutiny traditional theories of wire sawing, in which the slurry acts as a lubricant. While these theories have some validity, our experiments and associated theoretical analyses seem to indicate that the particles themselves (and less so the fluid) are the main entities that dictate the wire-ingot gap.

Möller (2006) and Baghavat *et al*. (2000) have conducted a lubrication analysis of the wire setup, but their analysis is actually inspired by the *foil bearing* lubrication theory (for *e.g*., flat magnetic tape recording head over an air bearing), which has a very high aspect ratio, flat (2D) geometry and is thus only slightly prone to lubricant loss at the sides.

In wire sawing, the 3D open configuration of the wire does not lend itself to a simple lubrication analysis. While the wire is pressed down into the groove, the large pressure generated at the bottom of the groove pushes the lubricant to the sides of the groove (where the pressure is very much close to ambient). Thus, if the lubricant were devoid of particles, the gap would be very quickly depleted of any lubricating fluid (*lubricant starvation*). Thus, only the particles can prevent the wire from actually touching the ingot: that is how the cutting process most likely occurs (lubrication is also incompatible with a cutting process since a lubricating film would prevent any direct wire-particle and particle-ingot contact). It is likely that the fluid serves mainly as a *particle conveyor* and as a *coolant*.

An additional observation of the sliding wire experiment has been the multiple interactions between particles. While bigger particles may contact the wire and ingot (especially on the sides of the groove), smaller ones still contribute as they roll over each other and enable a contact between the wafer and ingot (Figure 3).

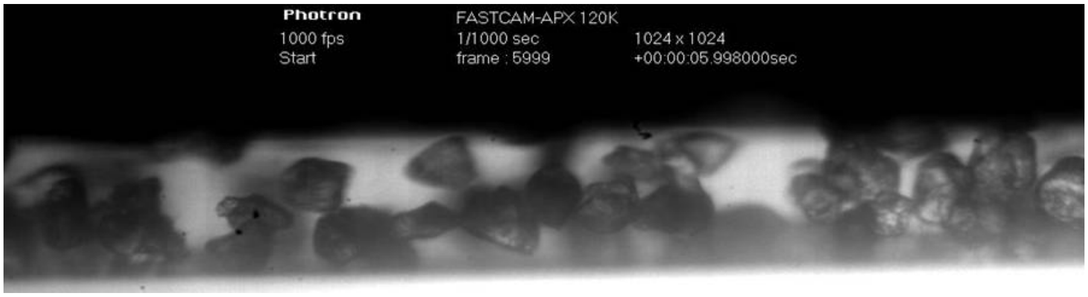

Figure 3: Sand crystals (100 microns to 500 microns) in the gap (about 500 microns in size) between the sliding wire and the groove bottom.

III. References

Möller H.J. 2006 "Wafering of silicon crystals," *Phys. Stat. Sol.* (a) **203**, No. 4, 659–669.

Baghavat M., Prasad V., Kao I. 2000 "Elasto-hydrodynamic interaction in the free abrasive wafer slicing using a wiresaw: modeling and finite element analysis," *Journal of Tribology* **122**, 394-404.