

FLUID MECHANICS OF WIRE SAWING

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ABSTRACT: The following paper investigates the fluid mechanical phenomena associated with wire sawing. While it is arduous to perform direct measurements within the microscopic gap between the wire and the ingot, similarity principles were used to scale up the measurement volume but a factor of 20 in order to facilitate the observations. Since the parameter space characterizing wire sawing is very broad, it is impossible to maintain perfect similarity. In order to palliate this drawback, two scaled up facilities were assembled, one based on a rotating wheel and one on 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.

Keywords: Fundamentals, Modeling, Wire saw, Fluid, Slurry, Lubrication

1 INTRODUCTION

Multi-wire sawing is the main slicing technique for large multi- and monocrystalline silicon crystals in the photovoltaic and microelectronic industry [1].

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, even if only qualitative, with wires, particles, and gaps in the millimeter-size range.

2 SCALED-UP WIRE FACILITIES

2.1 Similarity analysis

A physical phenomenon can generally be described by a number of dimensional parameters e.g. length, time, physical properties, etc and the use of a known theorem (the Buckingham's Pi 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 are guaranteed to be authentically reproduced (dynamic similarity).

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 between 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. We present the derived non-dimensional groups in Table I with their corresponding values in practice and in the sliding setups. In these groups, δ is the particle size, D is the wire diameter, E is the elasticity modulus of the wire, U is the wire speed, T is the tension force on the wire, ρ_f , ρ_a and ρ_w are densities of the liquid, the abrasive particles and the wire and μ_f is the viscosity of the liquid.

Table I: Non-dimensional groups and their corresponding values in practice and in sliding wire experimental setup

Non-dimensional group	practical	experimental
$\Pi_1 = \frac{\delta}{D}$	0.15	0.15
$\Pi_2 = \frac{T}{E \cdot D^2}$	3.1×10^{-3}	3.1×10^{-3}
$\Pi_3 = \frac{\rho_f \cdot U \cdot \delta}{\mu_f}$	2.0	2.0
$\Pi_4 = \frac{\rho_a}{\rho_f}$	0.9	0.9
$\Pi_5 = \frac{\mu_f \cdot U}{\sigma}$	6.8×10^3	6.8×10^3
$\Pi_6 = \frac{\rho_w \cdot D^2 \cdot U^2}{T}$	1.3×10^{-3}	1.0×10^{-5}
$\Pi_7 = \frac{\mu_f \cdot U \cdot D \cdot R}{T \cdot L}$	2.4×10^{-4}	2.4×10^{-4}
$\Pi_8 = \frac{T}{\rho_w \cdot U^2 \cdot L^2}$	0.4	0.003

2.2 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 1 millimeter).

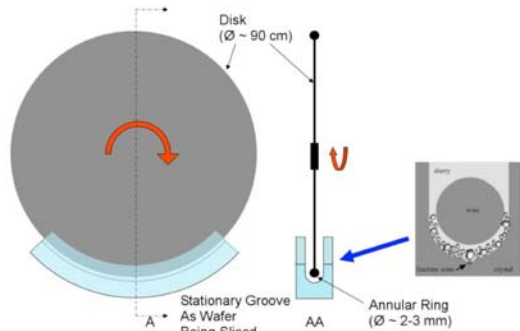


Figure 1: Rotating disk setup.

2.3 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 Plexiglas 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 1 mm/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.

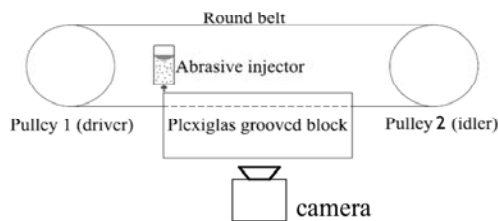


Figure 2: Sliding wire setup.

3 RESULTS

3.1 Rotating wheel

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

As the “wire” (the disk in this setup) presses onto the particles, due to the asymmetries in their shape and wire vibrations, 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. Smaller particles most likely remain at the bottom of the groove and act as a *fine-grit sand paper*. In other words, the direct cutting is most likely done by larger particles (Figure 3).

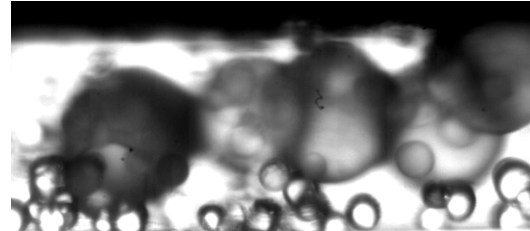


Figure 3: Example of particle configuration inside the cutting region (spherical particles). Wire is the black zone at the top and the ingot is at the bottom. Most of the smaller sized particles settle down over the cutting region while the larger ones are in contact with the wire and the sides.

Another peculiar phenomenon in this setup is that as the disk presses onto the particles, they “jump” with extremely high speeds (meters per second) towards the sides of the groove, blasting the surface of the wafers and therefore reducing their surface quality. These jumping events are probably coupled to the tendency of the larger particles to migrate toward the sides of the groove (Figure 4).

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Figure 4: Examples of abrupt jumps of particle to one side of the cutting region. As an example, the particle in the middle of top-left image is no longer present in the second image and therefore travels a distance of 1 mm in 1/1000 of a second (image sequence is left to right). The leftmost particle also jumps off with a lower velocity.

3.2 Sliding wire

The wire setup on the other hand, has 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 dynamics of wire-ingot gap.

Möller [1] and Baghavat *et al.* [2] have conducted a lubrication analysis of the wire setup, but their analysis is actually inspired by the *foil bearing* lubrication theory *e.g.* flat magnetic tape recording head over an air bearing, which is based on a flat (2D) geometry with a very high aspect ratio and is therefore 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*) due to this leakage. 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/debris 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 wire and ingot (Figure 5).

4 CONCLUSIONS

Our scaled-up facilities and tests have led to the following picture of the fluid mechanics of wire sawing:

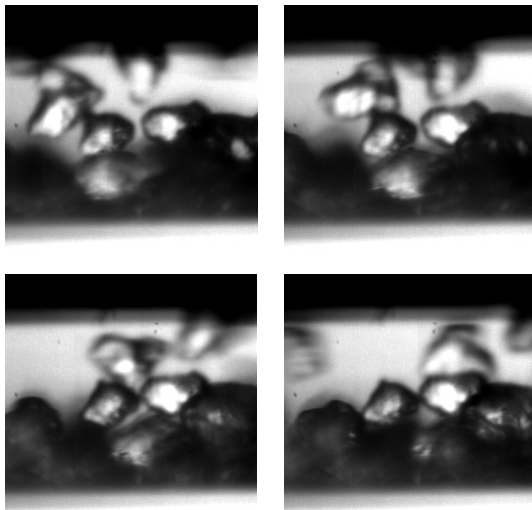


Figure 5: Example of particle configuration inside the cutting region (sand particles). Some particles are just floating and advected by the shear flow while many others sit on the ingot without any contribution to the slicing, mainly because the wire is in contact with larger particles at some other regions (image sequence is left to right).

(i) 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.

(ii) 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.

(iii) 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) unless pressed under the larger ones.

(iv) 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). However, particles within the gap strongly alter the basic flow.

5 REFERENCES

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