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ENDLESS DIAMOND WIRE SAW FOR MONOCRYSTALLINE SILICON CUTTING

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ABSTRACT

The multi-wire sawing of silicon using diamond coated wire is an important process in the semiconductor and photovoltaic industry. The process is performed by pushing the silicon ingot against a wire web that moves forwards and backwards. As the feed direction of the wire changes many times and the cutting speed is not constant, a proper investigation of the cutting process is very difficult to be performed. Aiming to experimentally investigate the multi-wire sawing of monocrystalline silicon (mono-Si), this work proposes a new test rig. For that, the requirements list is defined, and based on that, several conceptual solutions are proposed. The final solution is an endless wire saw that uses aerostatic bearing technology on its slides and rotatory bearings. Features of the built test rig are presented, as well as some results of experiments on process characterization and tracking the same diamond grains for wear analysis. The objective of tracking the same diamond grains for wear analysis is accomplished with the experimental setup.

Index Terms - Endless wire saw, wafering, diamond wire, silicon, diamond grit wear

1. INTRODUCTION

The multi-wire sawing is the principal technology responsible for slicing Si ingots into wafers. It has been widely used in the manufacturing of brittle materials such as silicon, sapphire and SiC. The cost to produce silicon (Si) wafers accounts for approximately 30-40% of the total solar cell fabrication cost, and about 80% of the world's solar cells in photovoltaic industry are currently fabricated using monocrystalline silicon [1]–[4]. Therefore, the multi-wire sawing of silicon is an important subject to be investigated, especially when it is necessary to reduce production costs to make the solar energy industry more viable.

A schematic representation of the multi-wire sawing technology is shown in Figure 1. A single steel wire is fed from a supply-spool to a take-up spool through a pulley, tension control unit and the wire guides. Multiple strands of a wire web are formed by winding the wire through the 500-700 parallel grooves on the wire guides. The wire web is pulled by the torque applied by the main drive and slave rolls, while at the same time, the Si ingot, glued to the holder, is fed against the moving wire web and sliced into hundreds of wafers.

The machine works based on the so-called pilgrim-mode: the wire is set in motion in one direction for several hundred meters, stopped, and then set in motion in the opposite direction for a shorter length. As the cutting direction and cutting speed of the wire change during the process (around 100 times in an usual wafering process), the resulting sawn surface that has been cut with constant speed is distributed in very thin lines (1 mm wide in this example).

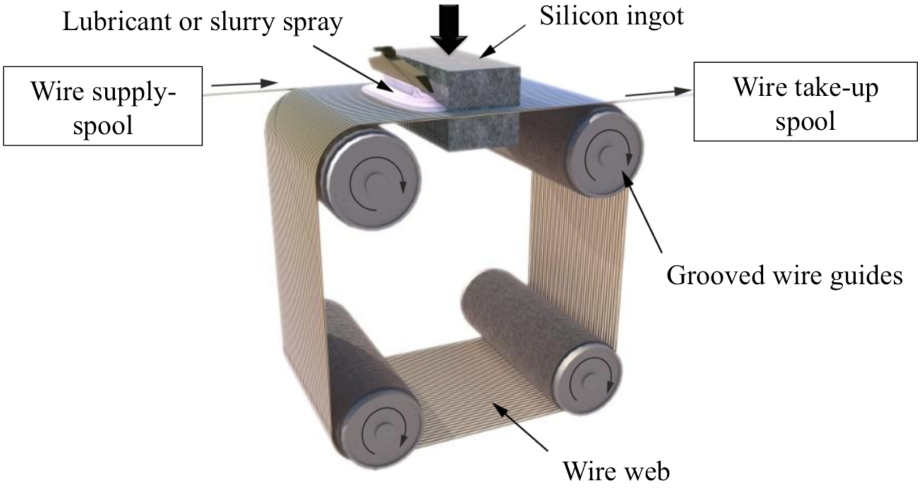


Figure 1 – Schematic representation of multi-wire sawing of silicon wafers. (adapted from [5])

The two main technologies used nowadays for Si wafering are Multi-Wire Slurry Sawing (MWSS) and fixed abrasive Diamond Wire Sawing (DWS). In the first case, the cutting is achieved by silicon carbide (SiC) abrasive slurry, typically oil or polyethylene glycol based, which is supplied through nozzles over the wire web and carried by the wire into the sawing channel. In the DWS process, the cut is done using a piano wire, which is electroplated with diamond grits that serve as fixed cutting edge (Figure 2), and the slurry is replaced here by a coolant fluid such as water.

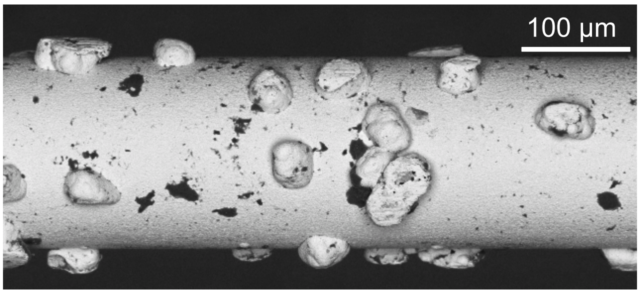


Figure 2 – SEM picture of electroplated diamond wire.

The diamond wire sawing technology exhibits advantages over the slurry, Table 1. Based on these advantages, DWS technology has been gaining industrial attention because of its potential for two to three times higher productivity and the potential to recycle the material removed from the kerf. The silicon chips that are cut away in the fixed abrasive process are clean and can be more easily recycled when compared to the slurry process [6]–[8].

Table 1 – Comparison between multi-wire sawing technologies. (based on [6], [7])

	MWSS	**DWS**
Cutting speed	10 – 20 [m/s]	10 – 20 [m/s]
Feed speed	0,3 - 0,5 [mm/min]	> 1 [mm/min]
Wire consumption	300 – 500* [km]	≈5** [km]
Cutting time	8 – 13 [h]	2 – 3 [h]

*The high consumption of wire in the slurry process is due to the damage done by the loose abrasives on the wire. **The diamond wire can be used up to 4 times before its end of life.

Although both sawing technologies are currently used in the industry, a fundamental understanding of the underlying process is still missing for DWS. Consequently, optimization of the wire sawing process is carried out largely based on experience and trial and error [8]. Moreover, since the industrial wafering process is done reversing the cutting direction (pilgrim-mode), correlating the non-constant wire speed to the generated wafer surface can be not reliable and very difficult to be performed. Moreover, as thousands meters of wire are used in one multi-wire cut, investigations on tool wear are difficult and usually done by sampling. At the Precision Engineering Laboratory (LMP/UFSC), Modesto [9] investigated the sawing process of green advanced ceramic plates with alternating cutting speed and direction, employing an electric scroll saw. In her work, there was also no practical way to evaluate the grit wear correlated to the cutting conditions.

Based on the mentioned difficulties found in the reversing diamond wire sawing, this work proposes an endless wire saw test rig, which works with a short segment of diamond wire and constant cutting speed. The advantage concerning the endless wire setup is the fact that the cutting speed (v_c) and feed speed (v_f) can be kept constant during the cut. With the looped wire it is even possible to follow the same wire section to analyze the wear progression of a group of abrasive grits after every cut, which in the case of a spool-to-spool setup would be practically impossible.

A few works about endless wire sawing can be found in the literature (see Table 2). Although these works investigated the DWS process, they do not contemplate cutting speeds higher than 20 m/s and wire diameter smaller than 500 µm for mono-Si. Industrial wafering machines are currently working with speeds that reach up to 30 m/s and wires with outer diameter (OD) down to 80 µm [10], which represent cutting conditions very different from those presented in Table 1. Additional to that, in all referred cases wires were firstly welded in looped-shape without any abrasives, and then coated with diamond grains in a self-made way.

Table 2 – Endless wire saws referred in literature.

Author	**Material Cut**	**OD [µm]**	v_c **[m/s]**
Hardin et al. [10]	Wood	300	≤ 20
Meng et al. [11]–[13]	Granite, Al_2O_3/TiC and mono-Si	500	≤ 20
Gao et al. [14]	Granite	800	≤ 20
Subbiah et al. [15]	Mono-Si	140	≈ 2

2. DESIGN OF NEW TEST RIG

The device was designed based on the Pahl & Beitz methodology [16]. The product development process is detailed in the following items.

2.1 Task Clarification

In this process, statements about the test rig such as functionality and performance were raised. Based on these descriptions, requirements were defined and multiple solutions for each function were proposed. As result, the list of the function requirements for the novel test rig were defined as follows:

- cut to be performed with constant wire speed;
- use of small segments of diamond wire;
- possibility to find the same diamond grains for wire wear investigation;
- low waste of workpiece material;
- possibility to increase cutting speed higher than 30 m/s;
- possibility to use different cutting fluids;
- possibility to change distance between rotatory axes to control eventual wire vibrations;
- clear vision of the cutting gap and wire bow;
- controllable wire tension;
- avoidance of non-cutting wire wear (damage caused by the wire-wire contact).

2.2 Conceptual Design

Based on the requirements list, the endless wire saw test rig could be built by the reconfiguration of an ultra-precision machine tool built previously at LMP/UFSC by Stoeterau [17]. The machine is fully based on aerostatic bearing technology and features 2 axes of movement and a 3rd positioning axis (see Figure 3 – a). The machine has two cylindrical guideways in the **z-axis**. On each of them, 2 linear aerostatic sleeves (AS) serve as the basis for two cylindrical aerostatic guideways with 2 linear AS in the **x-axis**. An aerostatic yate bearing (rotatory bearing) is responsible for the **c-axis** movement. A spare yate bearing was also available to be used for the machine reconfiguration.

The selection of aerostatic bearing technology for the endless wire saw test rig ensures low friction on the bearings and slides, provides high accuracy on the movements and allows direct measurement of the wire tension and feed force, which is desirable for this research on DWS.

In order to provide constant wire speed, it was defined that the wire saw test rig should have a looped diamond wire (in ring shape) installed around two pulleys attached to the mentioned rotatory aerostatic bearings each. Based on the necessities of having adjustable axis distance

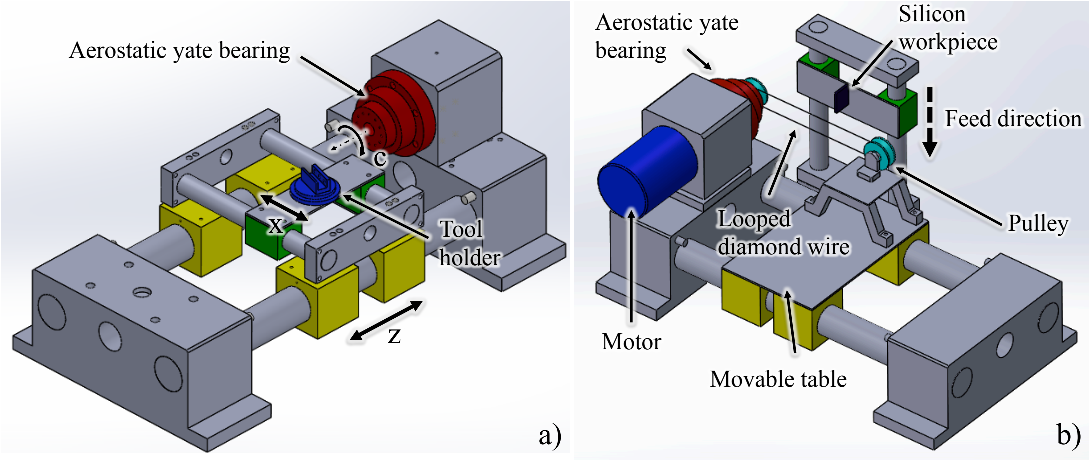


Figure 3 – a) Ultra-precision machine tool for single point turning.
b) Proposed conceptual solution #1.

and controllable wire tension, one of the rotatory bearings should be fixed and the other one movable on the z-axis.

Three concepts were suggested (differing in axis characterization, feed system and cutting movement) as follows:

- ***conceptual solution #1***: vertical linear movement of workpiece towards vertically aligned diamond wire, Figure 3 – b;
- ***conceptual solution #2***: lateral linear movement of workpiece towards horizontally aligned diamond wire, Figure 4 – a;
- ***conceptual solution #3***: vertical curved movement of workpiece towards vertically aligned diamond wire, Figure 4 - b.

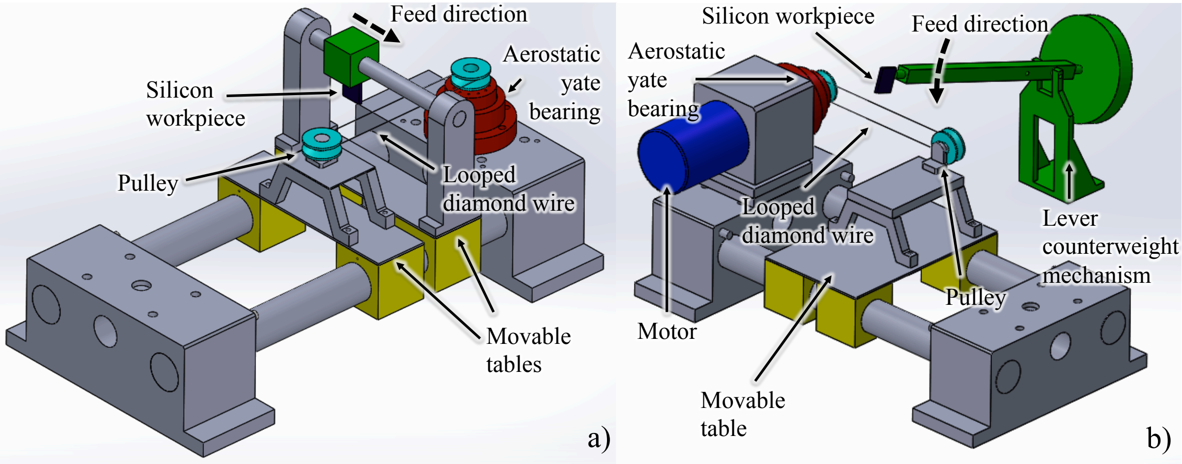


Figure 4 – a) Proposed conceptual solution #2. b) Proposed conceptual solution #3.

2.3 Embodiment and Detailed Design

The conceptual solution selected was #1. Some additional features were added to the selected conceptual solution, as follows (see Figure 5):

- workpiece feed speed controlled by counterweight;
- movable table for installing the looped wire;
- tension of the wire done by pressure-regulated pneumatic cylinder and controlled by spring deflection;
- use of incremental infeed of workpiece, which also defines the thickness of cut wafer;
- wire motion done by an electric-driven Professional Instruments (PI) Blockhead spindle.

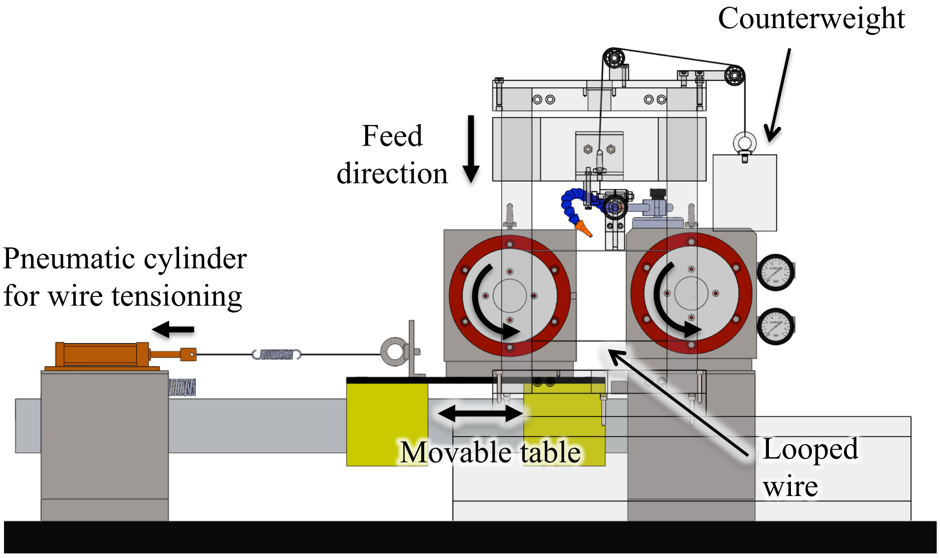


Figure 5 – Endless wire saw conceptual solution (front view).

The movement axes of the test rig are shown in Figure 6. They were defined as: **y-axis** for workpiece feed direction, **a** and **a'-axis** for rotatory motion of the discs, **z-axis** for the workpiece infeed and **x-axis** for installing and tensioning the looped wire.

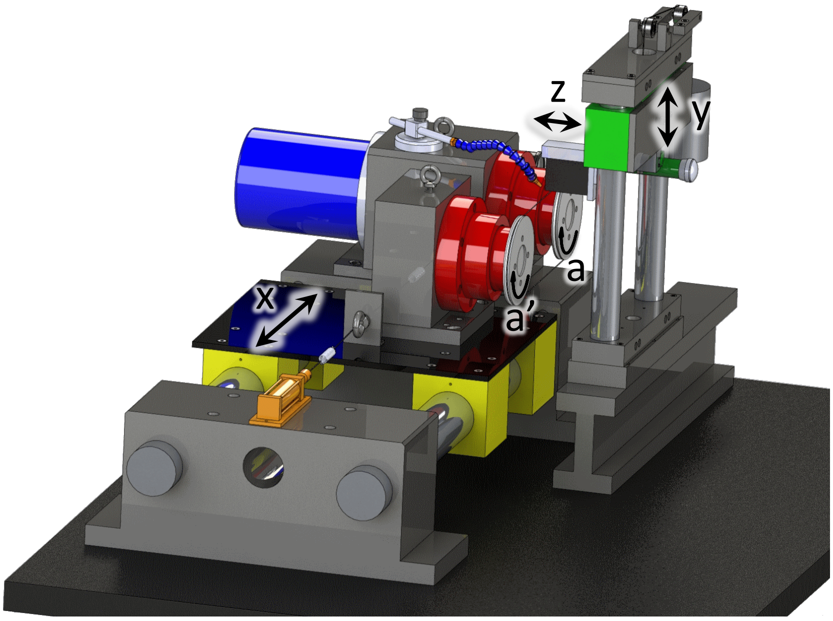
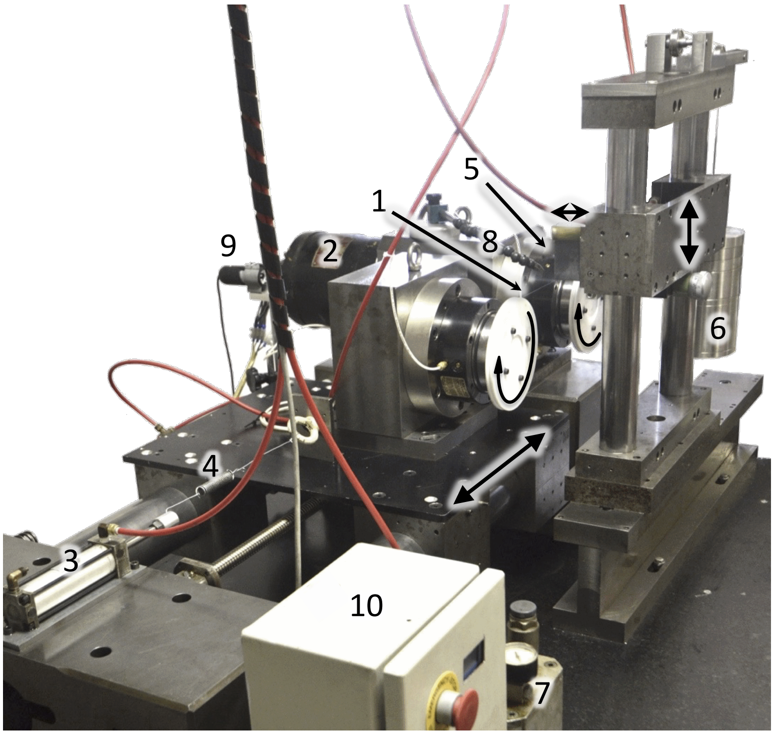


Figure 6 – Endless wire saw conceptual solution (3D view of virtual prototype).

3. FEATURES OF ENDLESS WIRE SAW TEST RIG

Based on the presented final design, the endless wire saw test rig was reassembled. The test rig, shown in Figure 7, features a looped diamond wire that spins around two aligned grooved Teflon discs (a and a'-axis) mounted on rotatory PI Blockheads (yates bearing): one on the fixed mount, direct driven by a controlled electric motor, and the other one on the linear aerostatic guide (x-axis). The wire tension is applied by a pneumatic cylinder and controlled by the deflection of a spring connected to movable table that supports the rotatory aerostatic bearing. The controlled electrical AC motor permits the adjustment of the wire speed up to

26 m/s. The workpiece is mounted on the vertical aerostatic slide (y-axis) and pushed with a constant force against the wire by gravity.



1. Diamond wire
2. Electric driven blockhead
3. Pressure-regulated pneumatic cylinder
4. Tension spring
5. Workpiece
6. Counterweight
7. Cutting fluid reservoir
8. Cutting fluid spray
9. Recording camera
10. Control panel

Figure 7 – Endless wire saw test rig.

As defined in the requirements list, the clear visualization of the cutting gap has been achieved. The cut is recorded by a Dino-Lite™ camera, so that the deflection of the wire can be measured as the wire bow angle θ (see Figure 8). The feed force is defined by counterweights, the wire speed by the control panel, and the wafer thickness is set by an adjusting screw.

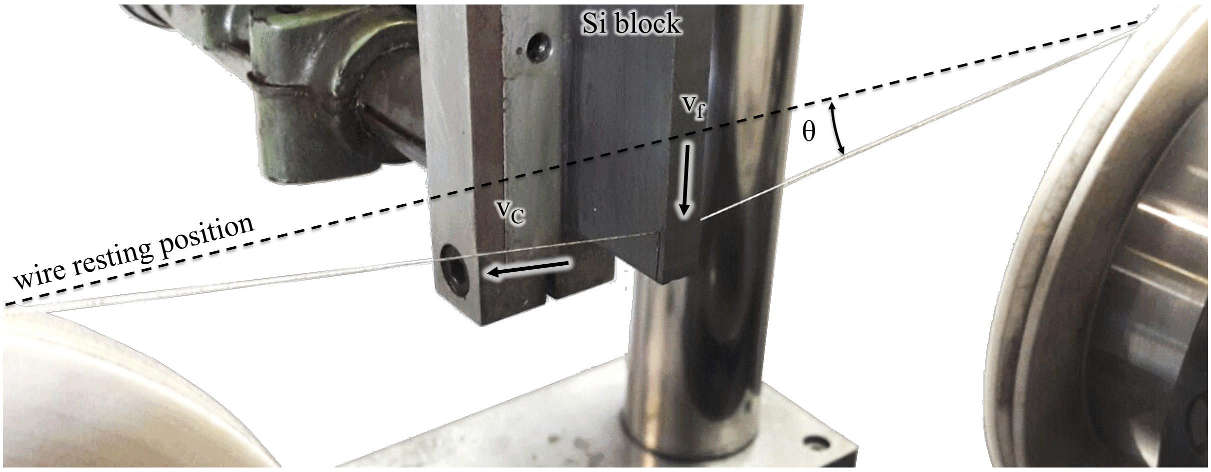


Figure 8 – Silicon block being cut – wire bow angle in detail.

4. EXPERIMENTS AND RESULTS

A single cut experiment is performed on the endless wire saw as follows: firstly, a segment of diamond wire (in the range of 1 m) is welded in looped shape by the upset welding device that was developed at LMP facilities by Knoblauch [18]. The burr at the welded joint is sanded so that its diameter becomes smaller than the wire outer diameter. The looped wire is installed around the Teflon discs by positioning the movable PI Blockhead closer to the fixed one. The wire tension is set by the pneumatic cylinder and controlled by the deflection of the helical spring. The normal force (F_n) is set by removing counterweights and measuring the force that the silicon block exerts on a calibrated scale. Once F_n is set, the thickness of the to-be-cut wafer is set using an adjusting screw (z-axis in Figure 8). The motor is turned on and its rotation is configured on the control panel (motor rotation is calibrated with a tachometer). The workpiece is then positioned close to the wire and left loose to move downwards (y-axis), so that the cut is performed.

In order to evaluate the test rig, two sets of experiments were both performed using electroplated diamond wires with OD = 350 µm and no cutting fluid (dry cutting). The first set was done to characterize the endless wire saw. The goal was to find the relationship between the normal force (F_n), wire speed (v_c) and workpiece feed speed (v_f). Sawing experiments with different cutting parameters were performed for the machine characterization. For each combination of cut parameters presented in Table 3, one cut and two replicas were performed (total cuts performed = 30).

Table 3 – 1st set of experiments – cutting parameters.

F_n [N]	v_c [m/s]			
	7,45	*13,7*	*19,97*	*26,21*
2,04		X		X
2,90		X		X
4,16	X	X	X	X
4,62		X		X

For each cut, a slice of mono-Si with 50 mm height (“h” in Figure 9) and thickness of approximately 1 mm was sawn by an unused (new) diamond wire in looped shape with total length of 1 m.

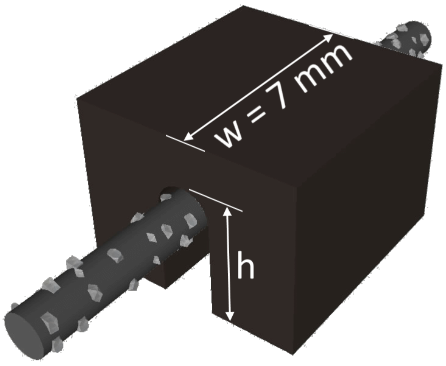


Figure 9 – Dimensions of the mono-Si workpiece.

The videos recorded from each cut were then post-processed, and an average feed speed is calculated from the 50 mm long sawn workpiece. The mean feed speed value from 3 cuts is presented in Figure 10 with the corresponding measurement uncertainty (confidence interval of 95%).

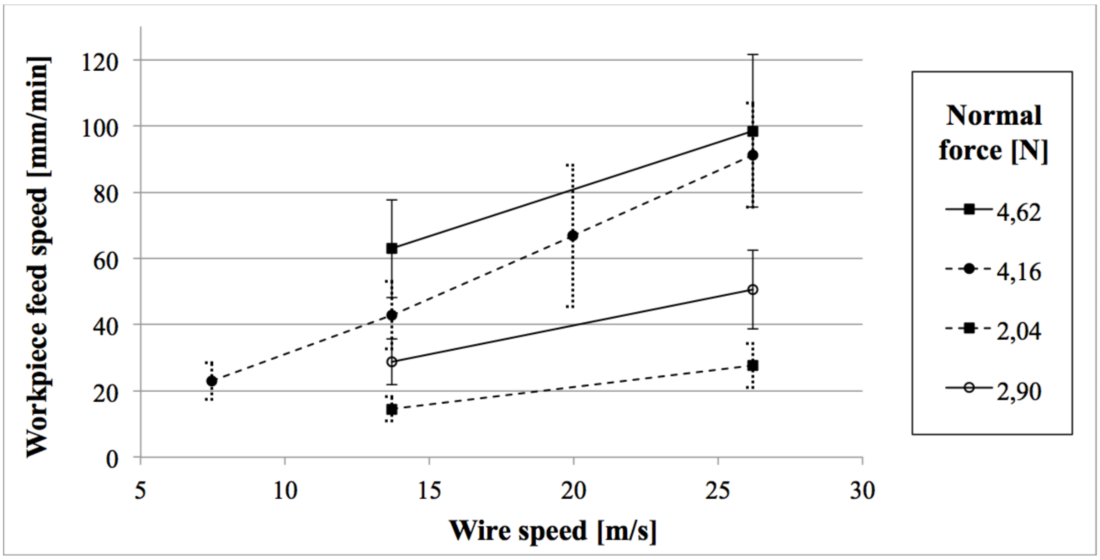


Figure 10 – Feed speed results from the cutting experiments.

For the same normal force, the feed speed increases proportionally with an increase of the cutting speed, Figure 10. Since the presented data follows approximately a linear proportion, lines were drawn to connect the measured points. Based on the interpolation of the results from the 1st set of experiments, a contour map was created in order to show the feed speed (v_f) in a (F_n) vs. (v_c) graph, Figure 11.

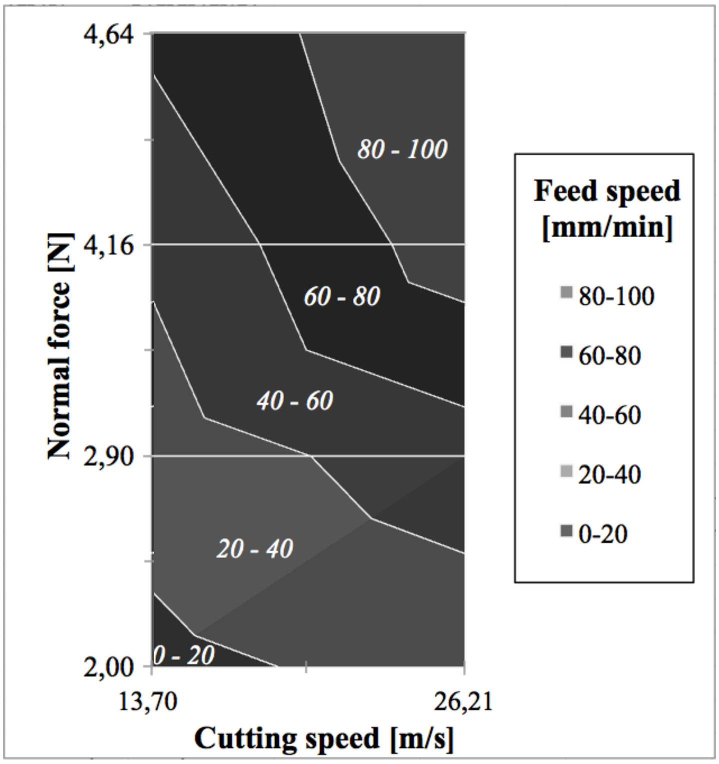


Figure 11 – Contour map of feed speed related to v_c and F_n.

This graph provides useful information for the user to find out the approximate normal force that should be applied to achieve a specific feed speed.

The second set of experiments was performed aiming to investigate the wear progression of the diamond wire. For that, a 2 mm-section of an unused looped diamond wire was analyzed under the scanning electron microscope (SEM). The wire was then used to saw mono-Si workpiece. Later on, the same section of the wire was analyzed again under the SEM, showing the same diamond grains after cut, situation that was proposed in the requirements list. The same group of diamonds are shown after h = 350 mm and h = 642 mm of sawn material, Figure 12.

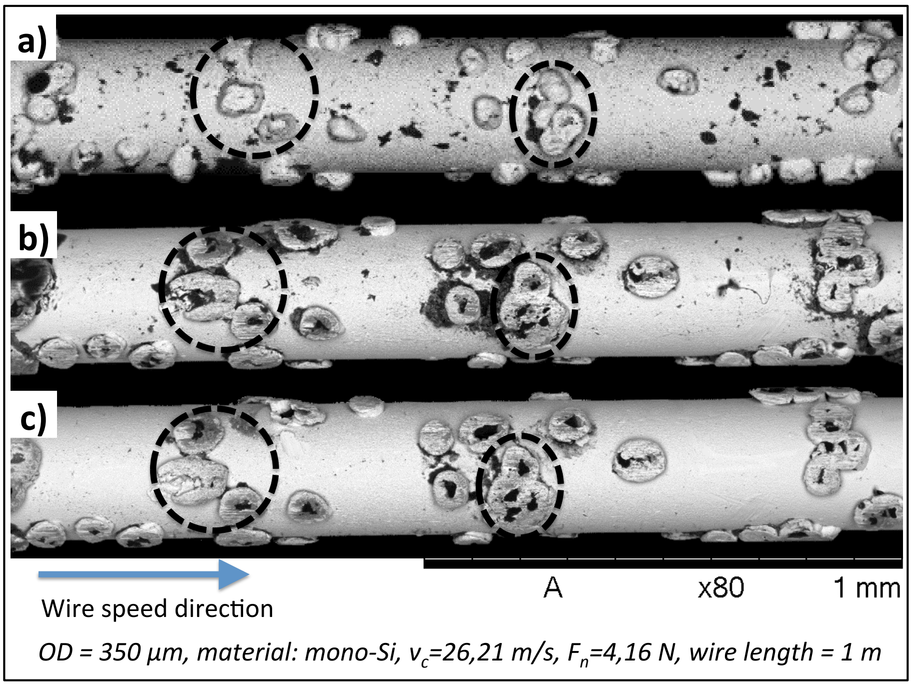


Figure 12 – Wear progression of a diamond wire segment: a) new wire, b) after cutting 49 cm^2, c) after cutting 90 cm^2.

5. SUMMARY AND CONCLUSION

The development of a new endless wire saw test rig has been proposed to investigate the sawing of mono-Si. The test rig requirements were defined, and from that, three conceptual solutions using aerostatic bearing technology were proposed. The final design was defined to work with linear vertical movement of the workpiece, and feed movement done by counterweight system.

Two sets of experiments were carried out to test the machine capabilities. Results of the workpiece feed speed depending on the normal force and cutting speed were presented. The proposed requirement of tracking same diamond grits for wear analysis was also accomplished with the experimental setup. Next steps related to this test rig will be performing cutting experiments to investigate the wear progression of diamond coated wires, the surface integrity of mono-Si sawn workpieces and the cutting force of the process.

6. ACKNOWLEDGEMENTS

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