COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1780
NUMERICAL MODELING OF A ELECTROPLATED DIAMOND WIRE FOR CRYSTALLINE SILICON MACHINING

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Abstract. *The continuous and growing demand for the use of renewable sources for energy generation has resulted in an increase in studies and research on the manufacturing process of solar panels, both in optimizing their energy efficiency and in production control to reduce manufacturing costs. The costs related to the cutting process represent about 50% of the total manufacturing cost, while raw materials contribute around 40% of the total cost. In this sense, research on crystalline silicon machining processes is fundamental to obtain a component with higher quality and optimized process parameters, allowing the reduction of the costs. Thus, the application of computational modeling of the machining process can assist in decision-making regarding process parameters without a long and costly experimental stage, thereby reducing production time. This paper proposes the modeling of the cutting tool used in the processing of crystalline silicon in Python code: the electroplated diamond wire. In order to obtain a model that is faithful to the real tool, the main properties of the diamond wire were implemented into the model: abrasive density, abrasive size, abrasive rake angle, wire core diameter, and outer diameter. Two types of industrial diamond wires were generated in order to evaluate the accuracy of the proposed model. For the first industrial tool, the use of polar coordinates and conical abrasives with a log-normal distribution of rake angle (φ) between 55-75° and a grain size varying between 30-45µm were attached on a wire and bonding layer, limiting them to an outer diameter of 350 µm. The distribution of the abrasives on the wire mesh was performed using the Monte-Carlo statistical method to obtain an abrasive density of 60 abrasives/mm², and the inner diameter was defined at 250 µm. As for the second type of diamond wire, the abrasive grain size was according to norm D76, outer diameter of 450 µm, abrasive density of 210 abrasives/mm² and distribution of rake angle stablished at 55-75°. The results show that all of the aforementioned characteristics converge to a modulus average that coincides with the characteristics indicated by the industrial suppliers of the diamond wires, which allows the use of the model for machining simulations according to the desired cutting tool type. Thus, the influence of these characteristics can be studied in order to quantify their effects on the machined surface quality of the crystalline silicon, and thus to optimize them to obtain minimum surface roughness and subsurface damage which result in greater efficiency of the final product.*

Keywords*: sawing process, brittle material machining, cutting tool modeling, photovoltaic industry.*

1. INTRODUCTION

1.1. Overview and objectives

Due to the increasing concerns about climate change and the environment, the search for renewable energy sources as an alternative to conventional sources has become essential and strategic for socio-economic development. In this new scenario, the search for renewable sources that presents low greenhouse gas emissions has been an important focus discussed by many researchers, especially regarding the economic viability involving the manufacturing of the components that compose the energy conversion systems. Among the alternatives of exploitable renewable energy sources, the solar energy is one of the most promising viable options, as it is forecasted to be responsible for 60% of the renewable energy generation capacity on a global scale (ITRPV, 2022).

Regarding solar energy based on photovoltaic technology, the material widely used in the production of solar cells is crystalline silicon, due to its semiconductor and optical properties that result in a high efficiency capacity for generating electrical energy when exposed to sunlight. Moreover, the crystalline silicon has high abundance, composing about 27% of the minerals found on the Earth's surface (SUZUKI et al., 2017). However, a significant portion of the costs involved in its manufacturing is in the cutting process of high-purity crystalline silicon ingots into thin slices with a thickness in the order of 100 µm, so-called wafers. This cutting process is based on imposing the silicon ingot against a web of multiple steel wires with the supply of an abrasive suspension (Wire Slurry Saw - WSS), so that the concomitant movement of the ingot and cutting movement promoted by the wire web added to the multiple abrasives-material contacts produced allow to obtain hundreds to thousands of silicon wafers in a single pass (COSTA et al., 2020; WU, 2016).

Another approach to obtaining silicon wafers is the use of wires with diamonds attached on the surface of a steel wire (Diamond-Coated Wire Saw - DWS), whose bonding can be electro-deposited, resinoid, or brazed (COSTA et al., 2022). For this case, there is the possibility of using a lubricating-coolant fluid during machining, in addition to increasing the material removal rate by up to 3 times when compared to the production of wafers by WSS (WALLBURG et al., 2022). However, the use of DWS can compromise the efficiency and lifespan of solar panels due to the subsurface damage, such as nucleation and propagation of microcracks that penetrate the subsurface, high surface roughness values, formation of amorphous layers due to phase transformation of the material, residual stress, among other damage to surface integrity (COSTA et al., 2020).

Considering the aforementioned aspects, the selection of machining tool parameters is fundamental to optimize the interaction abrasive-workpiece in order to reduce the damage introduced on the sawn surface such as microcracks and craters, to preserve the mechanical properties of the crystalline silicon and, consequently, improve the efficiency of the solar panel. For that, the main characteristics of the diamond wire were considered and two different types of industrial cutting tools were modelled using an in-house software to generate a tridimensional diamond wire. The evaluation of each parameter was made and the results were compared with the specifications provided by the suppliers.

1.2 Research background on the modeling and simulation of diamond wire sawing

The use of computational tools to model and simulate processes in order to predict results is increasingly present in both industrial and scientific contexts, allowing for the optimization of production parameters and, consequently, reducing time leads and manufacturing costs. Thus, the application of simulators for the diamond wire cutting process can assist in achieving a subsurface with low presence of microcracks and damage without the need for extensive experimental testing, as well as the prediction of surface roughness and others characteristics of the surface integrity.

For the modeling of the diamond wire, Chung et al. (2014) proposed a mathematical mesh method using matrices, where the distribution of the abrasives follows a log-normal distribution and their positions were determined using polar coordinates. For this way, important parameters of the actual cutting tool can be implemented in the simulation, such as abrasive size, rake angle, internal and external wire diameters, and bonding layer thickness.

Different approaches have been employed for the simulation algorithm of the kinematic process, depending on the desired cutting conditions that the researcher aimed to simulate. Gao et al. (2019) theoretically analyzed the relationship between the average cutting depth of abrasives at different positions on the diamond wire surface and the main cutting parameters as: wire cutting speed (v_c) and feed rate (v_f). The results showed that there is an increasing and nonlinear relationship between the average cutting depth and the critical ratio, calculated following the expression (v_f/v_c) that is an adaptive approach to estimate the undeformed chip thickness (h_{cu}) from the grinding process (KLOCKE, 2008).

On the other hand, Li et al. (2020) aimed to predict the trend of variation of the average surface roughness along the feed direction of the workpiece when varying the v_c and v_f. The autors consolidated a mathematical simulation model for machining of polycrystalline silicon using an electroplated diamond wire. The authors concluded that there is a power function relationship between the average surface roughness in function of the critical ratio (v_f/v_c), feed rate, and cutting speed.

Finally, with the aim of simulating subsurface damage and correlating cutting parameters with microcrack characteristics, Gao et al. (2021) proposed a mathematical model for representing the diamond wire and developed an algorithm for processing multicrystalline silicon. In this study, among other deductions, it was concluded that it is more prone to obtain material removal in the ductile regime of the material by increasing the v_c or decreasing the v_f, which results in a tendency to obtain a sawed surface free from damages. Compared to the cutting condition of v_c, the v_f has a greater impact on surface integrity of the sawed silicon.

2. MATERIALS AND METHODS

2.1 Industrial diamond wire

The first cutting tool (named as DW1) used in the present study consists of an industrial diamond wire (see Fig. 1a), with a nominal outer diameter of $Ø_{OD}$ = 350 µm and diamond abrasive ranging from 30 to 45 µm attached on the steel wire surface, provided by Saint-Gobain Abrasives. This diamond wire is compose of a steel wire with an internal diameter of $Ø_{int}$ = 250 µm, according to ASTM A228/A228M standard, with a Ni bonding layer containing electroplated diamond abrasives attached on the wire core surface. The abrasive density (η) was determined through image-processing using the open-source image processing software ImageJ®, obtained from the distribution available on the National Institute of Health website. The determined abrasive density for the diamond wire was about of η = 60 abrasives/mm².

On the other hand, the second cutting tool (named as DW2), shown in the Fig. 1b, has an external outer diameter of $Ø_{OD}$ = 450 µm with diamond abrasives, with a granulometry of D76 corresponding to the ranging of 66-86 µm, attached on the steel wire surface, provided by Insoll Tools Technology. While the earlier has only one steel core, this diamond wire is formed by stranded wires which result in an internal diameter of $Ø_{int}$ = 300 µm. A bonding layer based on an Ni-Cr alloy is used to fix the diamond abrasives on the wire core surface. For this diamond wire, the abrasive density (η) was estimated to be around of η = 210 abrasives/mm².

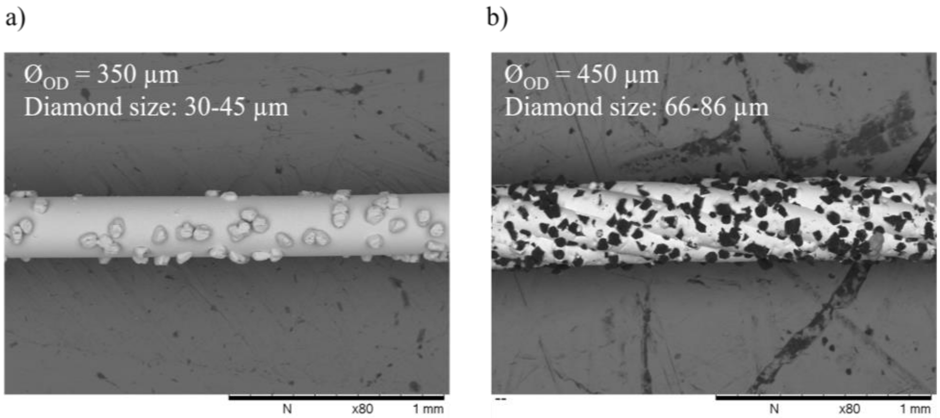

Fig. 1: a) Diamond wire (DW1); b) Diamond wire (DW2).

2.2 Modeling of the diamond wire

The modeling of the diamond wire was carried out based on the random distribution of the abrasives along the surface of the steel wire core, housed in a bonding layer – which it is related to the Ni layer of an industrial diamond wire. Based on previous work (CHUNG and LE, 2015), the surface of the wire was discretized into a mesh, whose abrasive positions can be identified by polar coordinates. Figure 2a illustrates the polar coordinate axis defined from the center of the cross-section of a pseudo steel wire core. Considering the real kinematics of the diamond wire sawing process, only the lower region of the wire remains active and in contact with the workpiece during the cutting simulation. Thus, the cutting tool model considers only half of the perimeter of the diamond wire that maintains effective contact for material removal, as follow the equation: $P_{wire} = \pi . r$.

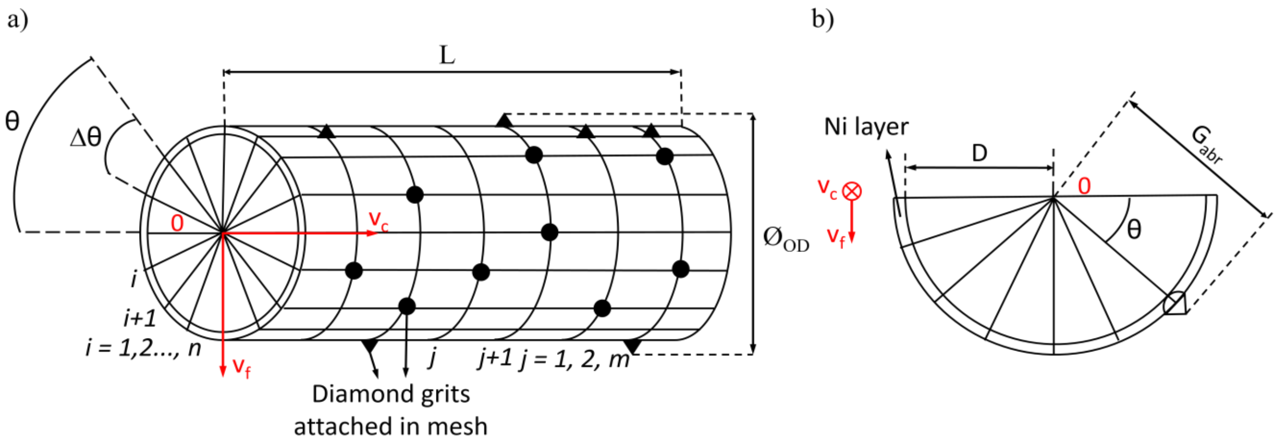

Fig. 2: a) Mesh model of diamond wire; b) Calculation model of polar coordinates of an abrasive with emphasis on the angle θ and distance G_{abr} from the origin point.

The mesh was defined as a matrix of null positions M = np.zeros(m,n), where n is the number of divisions in the axial direction (along the circumference of the wire) and m is the number of segments in the longitudinal direction (along the length). To ensure that the probability of an abrasive existing in position i x j (where i is the node in the n direction and j is in the m direction) is equal in both directions, the size of each node in the mesh must be the same (CHUNG and LE, 2015), as described by Eq. 1.

$$\frac{L}{m} = \frac{\pi * D}{n} \tag{1}$$

Therefore, L is the length of the wire in the direction of the cutting motion within a time interval Δt (for this study was considered value of Δt = 0.01 s) and D is the nominal outer diameter of the diamond wire. The probability of the existence of an abrasive lodged in a node of the mesh was calculated using the Monte Carlo method (MONTGOMERY and RUNGER, 2014). In this sense, if an abrasive is present at a position i x j, the matrix will have its null element replaced by the polar coordinates of the abrasive, identified by the angle θ of the abrasive position relative to the coordinate axis and the distance G_{abr} from the center of the axis to the tip of the abrasive edge, as shown in Fig. 2b.

2.3 Geometrical model of diamond abrasive

The abrasive is a fundamental element of the tribological system so that the material removal in the form of chips and, consequently, the surface formation meets the desired specifications for the final workpiece. Different abrasives models are proposed in the literature, so that simplified shapes involving the main geometries of crystals - e.g. cubic, octahedral, and tetrahedral - commonly found in diamond abrasives are possible. For this study, the geometry chosen for modeling the diamond abrasives was divided into two main parts. As shown in Figure 3, the abrasive has a conical section, in which the rake angle (φ) is defined as half of the edge angle; and a semisphere that is inserted within the bonding layer, whose radius varies in range between 1/3 and 1/2 of the size of the abrasive, as suggested by Zheng et al. (2021). Thus, the total size of the abrasive was denoted as d.

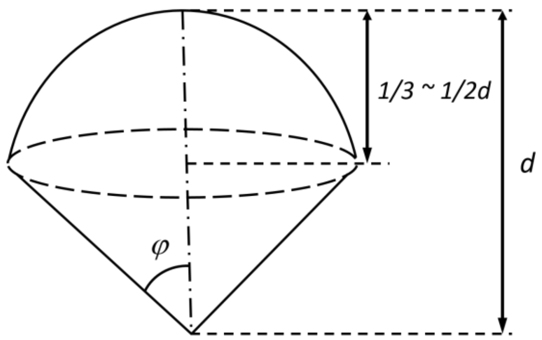

Fig 3: Geometric shape model of the abrasive. Adapted from Yin et al. (2021).

Both the distribution of the abrasive size and the range of rake angle (φ) follow a log-normal distribution (see Eq. 2), whose variables depend on the maximum and minimum values (subscripts as max and min, respectively) and the mean (subscript as med) of the parameter under study. Therefore, the 3σ probabilistic rule was used to calculate the standard deviation (σ) of the distributions, which ensures that 99.74% of the values are within the determined interval for each variable (YIN et al., 2021). Thus, the distribution curve of diamond abrasive sizes in the range of 30 to 45 µm and the exit angle in the range of 55º to 75º was obtained.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{(x-xmed)^2}{2(\sigma x)^2}} \quad x = d,\ \varphi \tag{2}$$

3. RESULTS AND DISCUSSION

For the validation of the diamond wires modeling, the main parameters that define the characteristics of the diamond wire as an abrasive cutting tool were analyzed, namely: grain size (d), grain rake angle (φ), and grain density (η). Since the calculation of the presence of abrasive grains at a given node in the mesh followed the Monte Carlo method, the histograms were plotted following a normal curve fitting to visualize the statistical distribution and random nature of each property analyzed, as shown in Figs. 4 and 5.

As shown in Fig. 4a, the rake angle (φ) for both diamond wires remained in range from 55 to 75°, which is in accordance with the abrasives used in cutting tools. It can be noted that the distribution of φ values followed a Gaussian curve, confirming that is possible obtain a randomness of the cutting tool using the modeling propose. The Figs. 4b and 4c show the abrasive sizes (d) of each cutting tool, revealing the values are also into the range established which are: between 30 and 45 µm for the DW1; and from 66 to 86 µm for the DW2. Similarly, the curves also followed a Gaussian curve. Moreover, the average values converge with the main parameters of the industrial diamond wires used in this study, indicating that the modeling process of the abrasive grains and their placements on the wire mesh follows the characteristic randomness, which is desired for abrasive tools. The calculation of the resulting standard deviation from the 3σ rule also remained consistent for the approach of the diamond wire modeling.

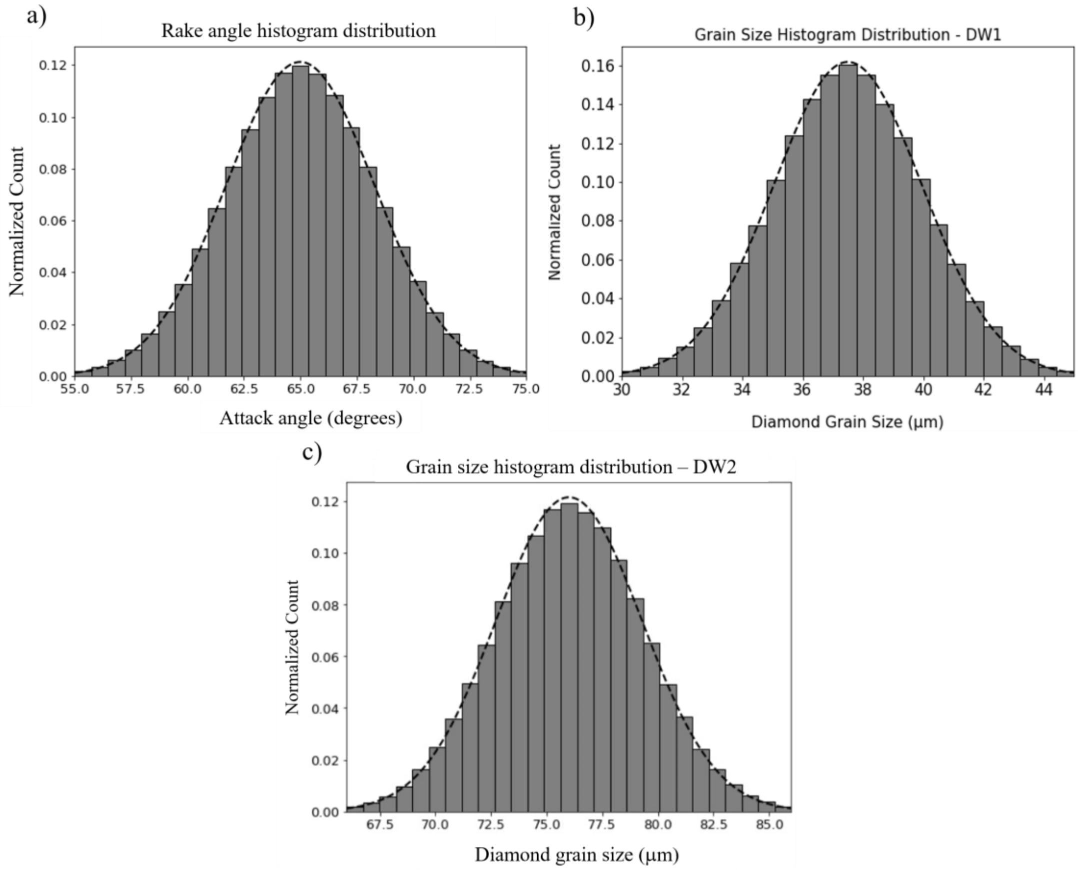

Fig. 4: Histogram distribution of: a) rake angle; b) grain size for DW1; c) grain size for DW2;

For the analysis of abrasive density (η) for both cutting tools, a quarter of the cross-sectional area (calculated as πD) of the diamond wires was segmented, so that the abrasive density could be calculated within a 0.25 mm x 0.25 mm square. This division was necessary because the size of the diamond wire's cross-section is larger than 1 mm, which prevented an area analysis in the mesh matrix of the wire. Thus, for a value of η = 210 abrasives/mm², an abrasive density of η = 52.5 abrasives/0.25*1mm² was calculated; for η = 60 abrasives/mm², a magnitude of η = 15 abrasives/0.25*1mm² was calculated. As observed in Figure 5, both averages values converged to the aforementioned values, indicating that the diamond wire model is in accordance with the main parameters of the industrial diamond wires used as references in this study.

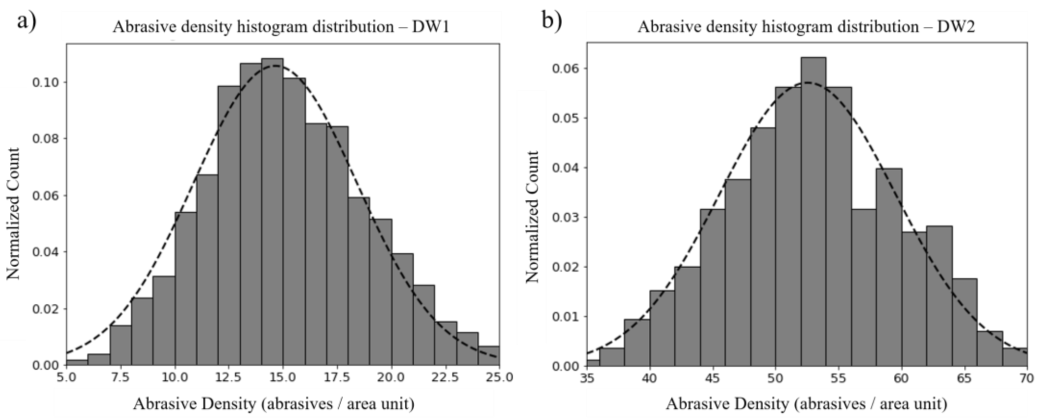

Fig. 5: Evaluation of the abrasive density distribution for the different diamond wires: a) DW1; b) DW2

Therefore, in order to improve the visualization of the diamond wires obtained by the modeling process proposed in this study, the 3D library of the Matplotlib package was used to illustrate a section of the wire mesh. The Fig. 6 show a section corresponding to a length of 10 times for each diamond wire diameter as well as the abrasives attached on the surface of this section allocated to predefined nodes from the constructed polar matrix. Additionally, a three-dimensional plot of the wire mesh in a planar format was also generated, allowing for a more accurate observation of the positions of the abrasive grains and its randomness. Thus, both models of the diamond wires are statistically truthful to the main characteristics evaluated and it can be used to simulate their influence during crystalline silicon machining.

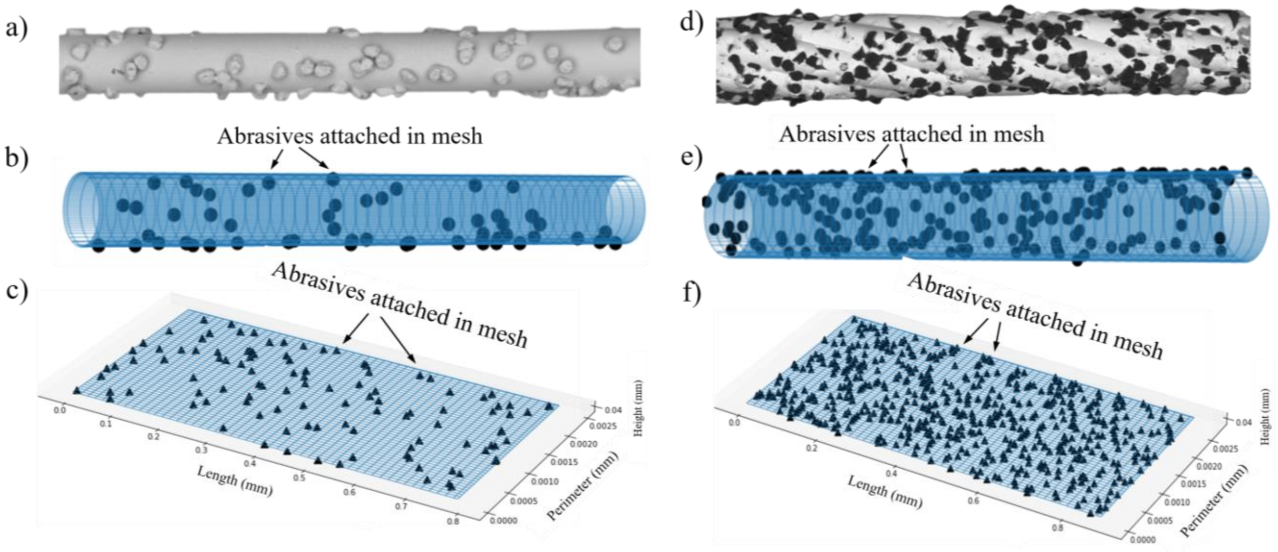

Fig. 6. Models of the diamond wires: a) SEM image of the DW1; b) cylindric model - DW1; c) plane model - DW1; d) SEM image of the DW2; e) cylindric model - DW2; f) plane model - DW2.

4. CONCLUSIONS

This study aims to modeling, characterizing and validating a computational method to generate diamond wire used in the machining of crystalline silicon wafer. As main parameters that influence the cutting process were considered and analyzed: abrasive density, diamond grain size, rake angle distribution and inner and outer diameters. Based in the results obtained, the following can be concluded:

(i) The application of Monte-Carlo method and log-normal distribution is a viable option to recreate the stochastic nature of abrasive grains attached on the surface of the diamond wire;
(ii) All the considered parameters converged to those provided by the industrial suppliers, consequently proving the efficiency of the model;
(iii) The parameters can be successfully changed as input variables to better represent the electroplated diamond wire selected for the machining process;
(iv) The model can be applied to simulate the effect of each parameter on the surface integrity of the crystalline silicon after applying the diamond wire sawing process, which can allow to optimize the quality as well as decrease the time and cost of solar panels manufacturing.

5. REFERENCES

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