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Peridynamic Modelling of Propagation of Cracks in Photovoltaic Panels

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Abstract

Photovoltaics (PV) is a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. Cracking in PV panels can cause performance degradation in PV panels. In this study, a new computational methodology, peridynamics is utilised to investigate the cracking behaviour in PV panels. Peridynamics is based on integro-differential equations, and it is a very suitable technique to model crack initiation and propagation. Majority of PV panels are based on silicon solar cell technology. Therefore, polycrystalline material behaviour of silicon is explicitly considered in the model. The numerical framework can be used to support the design of high-performant, long-lasting and fracture-resistant PV panels. The results can also be used to produce practical guidelines aimed to facilitate the decision of PV module rejection due to cracking during production.

Keywords: Polycrystalline Material, Peridynamics, Crack, Photovoltaics

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1. INTRODUCTION

Photovoltaics or photo-electric cells are commonly referred as Solar Panels. The urge to reduce carbon emission and to protect the earth, the dependency on the Solar Energy has increased in the last decades. The efficiency of the solar cell is defined by the active cell regions. Despite of investing billions of dollars to convert solar energy to electrical energy, it is equally important to understand the reasons that degrades the PV cell efficiency from damages or cracks that decrease the life span.

As early as 700 BC, people have harnessed the solar energy[1]. Around 1800 century, after several iterations, a French scientist Edmond Becquerel was credited for a breakthrough invention, where light can increase the current generation when two metals are submerged in a conducting solution[1]. Since then, many inventions, research papers and noble prizes have won in the race to develop a successful solar panel. Today solar panels are used in commercial buildings, handheld devices, household items and many more. The renewable source of solar energy has driven the countries to invest billions of dollars on mega solar farms and offshore floating solar systems to power-up the entire city or even parts of the country.

The three main categories of solar panels are monocrystalline, polycrystalline and thin-film solar panels. Among them, polycrystalline solar panels are ecofriendly, and the manufacturing cost is less when compared to their cousins monocrystalline and thin-film solar panels. At the same time, there are certain disadvantages over the others such as, the cell efficiency is around 12% to 14% and the life span is shorter than monocrystalline which is expected to be about 20 to 25 years.

The cell efficiency and the life span of the panels are determined by the percentage of active zones in PV panel. One of the reasons that causes inactive zones is due to discontinuities or crack that develops in silicon overtime due to the thermal expansion and contraction. Few numbers of damaged zones are caused during the manufacturing process, due to the soldering process.

The Silicon that acts as a semi-conductor in the PV cell undergoes photo-electric effect and produces DC current. The cell efficiency is dependent on the major ingredient, Silicon. Therefore, in this paper, we have addressed the behaviour of discontinuities, i.e., cracks, that reduce the cell efficiency in polycrystalline solar panels and investigated with the numerical model by considering the microstructures (grains), using peridynamics[2-7].

2. PERIDYNAMIC THEORY

2.1. Classical Continuum Mechanics and its limitations

Prediction of the mechanical behaviour of the material when subjected to external force has been the foundation of the structural analysis. Since 19th century the well-known Classical Continuum Mechanics (CCM) formulation has been very successful to analyses many problems, and the governing equation is in the partial differential form[8]

$$\rho(\boldsymbol{x})\ddot{\boldsymbol{u}}(\boldsymbol{x},t) = \nabla.\boldsymbol{\sigma} + \boldsymbol{b}(\boldsymbol{x},t) \tag{1}$$

where '$\rho(\boldsymbol{x})$' is the density of the material point '$\boldsymbol{x}$', and '$\ddot{\boldsymbol{u}}(\boldsymbol{x},t)$' denotes the acceleration of the material point '$\boldsymbol{x}$' at time 't'. Whereas '$\boldsymbol{\sigma}$' is the stress tensor and the body force that acts on the material point '$\boldsymbol{x}$' at time 't' is denoted by '$\boldsymbol{b}(\boldsymbol{x},t)$'. The basic concept of continuum mechanics is assumed that the material is continuous throughout the process.

Any material when observed at macroscopic level, can be considered as continuum. When a material is subjected to external load and it tends to react according to its material characteristics, and at some point, it fails in the form of various damage modes such as fracture. Since, the CCM formulation is based on the continuum concept, the governing equation given in equation (1) fail when the discontinuity occurs in the material[9]. Many studies on fracture mechanics have branched out from CCM to understand the fracture behaviour. Despite of succeeding in understanding the fracture behaviour, there are still limitations and challenges to identify cracks that propagate in complex manner.

This problem has been overcome by the recently developed PD formulation in the year 2000 by Silling in an attempt to deal with discontinuities. And today peridynamics is known as a new continuum mechanics formulation.

2.2. Peridynamics

At microscopic level, there are several factors that contribute to the mechanical properties, such as grain size, grain orientations, grain boundary conditions and many more. At the same time, all the above can play a vital role in crack propagation (crack path, branch, etc.) that develops on a material through time. PD equation is the reformulation of the equation of motion in solid mechanics, mainly developed to model bodies with discontinuities, such as a crack.

With contrast to CCM formulation, which is dependent on stress of the material points, the PD formulation is a function of displacement between two material points. The peridynamic formulation uses an integral equation, and the original peridynamic governing equation is based on Bond-Based interactions between two material points. The bond (interaction) forces are equal in magnitude and in the opposite directions[9].

$$\rho \ddot{\boldsymbol{u}}(\boldsymbol{x},t) = \int_{\mathcal{H}\mathrm{x}} \boldsymbol{f}(\boldsymbol{u}(\boldsymbol{x}',t) - \boldsymbol{u}(\boldsymbol{x},t), \boldsymbol{x}' - \boldsymbol{x})\, dV_{x'} + \boldsymbol{b}(\boldsymbol{x},t) \tag{2}$$

With reference to the equation 2 and figure 1, the $\mathcal{H}_x$ is the neighborhood of '$\boldsymbol{x}$' determined by the radius 'δ' known as horizon, '$\boldsymbol{u}$' is the displacement, '$\boldsymbol{b}$' is the prescribed body force density field, 'ρ' is mass density and '$\boldsymbol{f}$' is the pairwise force function exerted on the material point '$\boldsymbol{x}$'.

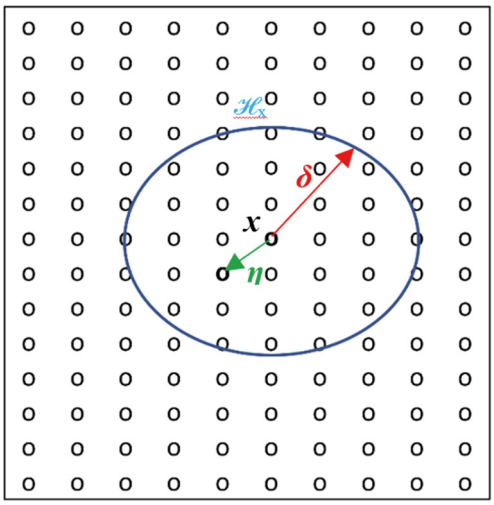

Figure 1: Peridynamic model of plate

Relative position vector is expressed as '$\boldsymbol{\xi} = \boldsymbol{x}' - \boldsymbol{x}$' and the relative displacement vector at time 't' is denoted as '$\boldsymbol{\eta} = \boldsymbol{u}(\boldsymbol{x}'t) - \boldsymbol{u}(\boldsymbol{x},t)$'.

$$f(\boldsymbol{\eta},\xi) = f(\boldsymbol{\eta},\xi)\frac{\boldsymbol{\eta}+\xi}{||\boldsymbol{\eta}+\xi||} \tag{3}$$

The pairwise force function of a micro-elastic material is derived from the micro-potential function '$w(\boldsymbol{\eta},\boldsymbol{\xi})$' which is written as.

$$f(\boldsymbol{\eta},\xi) = \frac{\partial w}{\partial \boldsymbol{\eta}}(\boldsymbol{\eta},\xi) \qquad \forall\, \boldsymbol{\eta},\boldsymbol{\xi} \tag{4}$$

For brittle materials, the pairwise force function is dependent on the stretch of the bond between two material points:

$$f(\boldsymbol{\eta}, \xi) = c(\boldsymbol{\xi}) s(\boldsymbol{\eta}, \boldsymbol{\xi}) \frac{\boldsymbol{\eta} + \boldsymbol{\xi}}{||\boldsymbol{\eta} + \boldsymbol{\xi}||} \tag{5}$$

Bond stretch can be represented as

$$s(\boldsymbol{\eta}, \xi) = \frac{||\boldsymbol{\eta} + \boldsymbol{\xi}|| - ||\boldsymbol{\xi}||}{||\boldsymbol{\xi}||} \tag{6}$$

The bond constant 'c' for a 2-Dimensional isotropic material can be expressed as.

$$c(\boldsymbol{\xi}) = \frac{6E}{\pi \delta^3 h(1-\nu)} \tag{7}$$

where, 'E' is the elastic modulus, 'h' is the thickness of the plate and 'ν' is the Poisson's ratio of the material. In 2-D analysis of Bond Based peridynamic model, the Poisson's ratio is limited to 1/3.

The critical stretch 's_0' of the bond can be derived from critical energy release rate G_c as.

$$s_0 = \sqrt{(4\pi G_c)/(9E\delta)} \tag{8}$$

3. POLYCRYSTALLINE SOLAR PANELS

Polycrystalline silicon (poly-Si) or Multicrystalline silicon (mc-Si) is highly pure and used in photovoltaic cells and electronics industry. It is one of the most preferred types of PV cells in the world today. It is usually in blue colour and the corners are squared edges. It is commonly seen on the roofs of the residential properties.

3.1. Silicon or Polycrystalline Silicon

Polycrystalline silicon or Silicon (Si) with atomic number 14, has density of 2329 kg/m^3 melts at 1414 °C and boils at 3265 °C. It is a hard, brittle crystalline solid with blue-grey metallic luster which is tetravalent metalloid and semiconductor. It was not discovered until 1823 by Jöns Jakob Berzelius[10].

Metallurgical grade silicon is 95 to 99% pure and it is mostly used in the process of aluminium-silicon alloy[11]. It improves the performance in casting thin sections and prevents the formation of cementite where exposed to outside air. It significantly improves the hardness of aluminium (Al).

3.2. Manufacturing process of polycrystalline silicon

Silicon is mostly accompanied by oxygen as silicon oxide (SiO_2)[10]. Crude silicon remains after removal of oxygen. The purification of silicon undergoes a chemical process known as Siemens process.

In this process, fragments of raw silicon are melted and poured into a square mold. The resultant material has improper crystal alignment, formed due to many bits of individual silicon crystal.

Pure silicon becomes an insulator at room temperature. However, but when the silicon undergoes doping process, it is electrically charged. This process produces negatively charged n-type semiconductor and positively charged p-type semiconductor. By joining p-type to n-type silicon produces DC electric current.

3.3. Working principle of solar cells

As mentioned earlier, PV cell is transforming solar energy to electrical energy. However, the working principle is not straight forward. The photon energy 'E' from the sun light is inversely proportional to the wavelength 'λ' of the light, which can be expressed as[12]

$$E = hf = \frac{hc}{\lambda} \tag{9}$$

where '$h = 6.626 \times 10^{-34}$ joules · s' is the Planck's constant and '$c = 2.998 \times 10^{8}$ m/s' is the speed of light. Therefore, from the inverse equation 9, the high energy photons have shorter wavelength and vice versa[12].

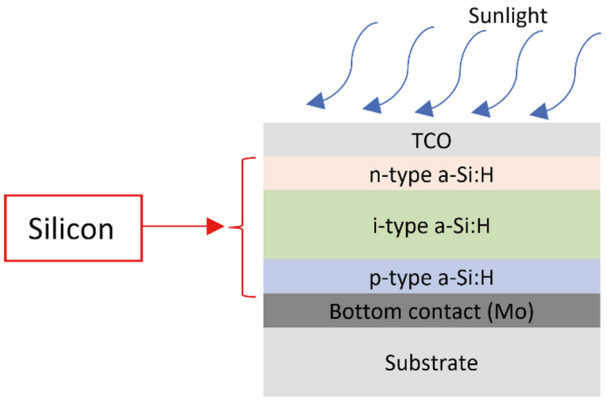

Figure 2: Working principle of solar cells

From the equation 9, constant '*hc'* can be rewritten in electron volt 'eV' and micrometer 'μm' as[12]

$$hc = 1.99 * 10^{-25} joules - m * \frac{1\ eV}{1.602 * 10^{-19}} joules * 10^{6} = 1.24\ eV - \mu m \tag{10}$$

Photon energy is calculated as E(eV) = 1.24/λ(μm)[12]. When the photon energy from sunlight hits the silicon layer in a solar cell, it creates flow of electron from n-type to p-type semi-conductor, resulting in photoelectric effect. Thereby, the DC current is converted to AC current with the help of inverters.

3.4. Grain boundaries in polycrystalline solar cells

Polycrystalline is referred to a solid that consists many small crystals known as grains. Grains are formed during solidification process and the boundary region where two grains meet is defined as Grain Boundary (GB). Grain Sizes (GS) in polycrystalline silicon is around 0.33 mm or 333 μm. GB and GS play an important role in determining the final character of the material. For example, coarse grain in a metal is more ductile that the fine-grained material which is brittle.

Figure 3: Randomly generated average grain size 0.33 mm or 333 μm

In a polycrystalline solar cell, the major ingredient is the silicon and it is in pure form. The difference in grain strength is caused during the manufacturing process where bits of silicon is melted and formed together. In return the bond strength within is grains is always varies when compared with the grain boundary strength, its either higher or lower. Grain boundary co-efficient (GBC) can be calculated as

$$GBC = \frac{GB}{GI} \tag{11}$$

where 'GB' is the grain boundary region and 'GI' is within the grains itself. The peridynamic analysis of crack propagation in polycrystalline PV panels are tested with three grain boundary conditions, which are GBC=1.0, GBC=0.5 and GBC=2.0.

4. CRACK PROPAGATION ON POLYCRYSTALLINE SOLAR CELL

In this numerical study, a 2-D sample plate with dimensions 5mm x 5mm and, initial notches (cracks) of 0.4 mm at the right and left edges, respectively, is considered as shown in Figure 4. The material properties of silicon are given as density of 2330 kg/m3 and elastic modulus of 138 GPa. Although the Poisson's ration (ν) of silicon is 0.4, in 2-D mode, Poisson's ratio value is assumed as constant at 1/3. Tensile load of velocity 25 m/s is applied at top and bottom of the plate. Total simulation time is 2.4 μs and each time-step size is 2 ns.

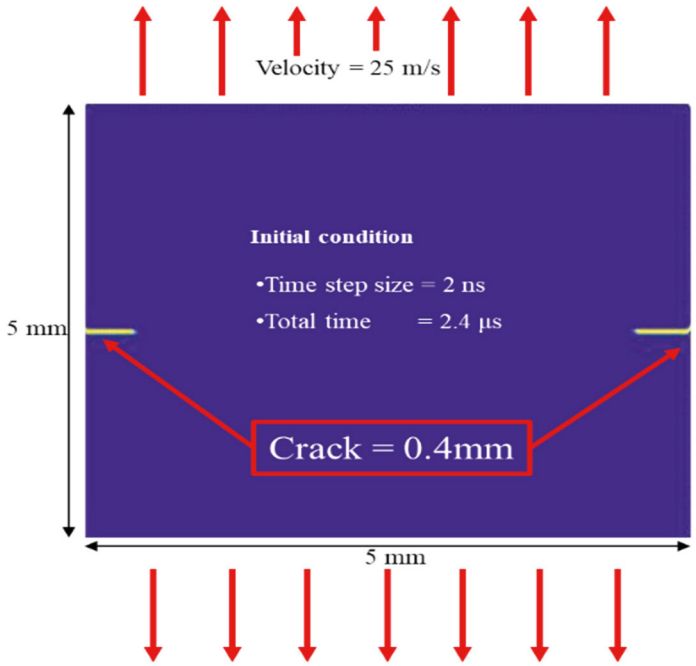

Figure 4: Initial condition of the polycrystalline silicon plate

The PD numerical modelling of polycrystalline silicon for this experiment was carried out using computational software MATLAB.

4.1. Case 1 –Without considering the microstructure

In most cases, structural analysis is carried out at macroscopic level and in general the grain structures are neglected as they are too small when compared to the actual dimension of the material. Figure 5 shows the simulation results of the crack propagation in the plate shown in figure 4, without considering the microstructure.

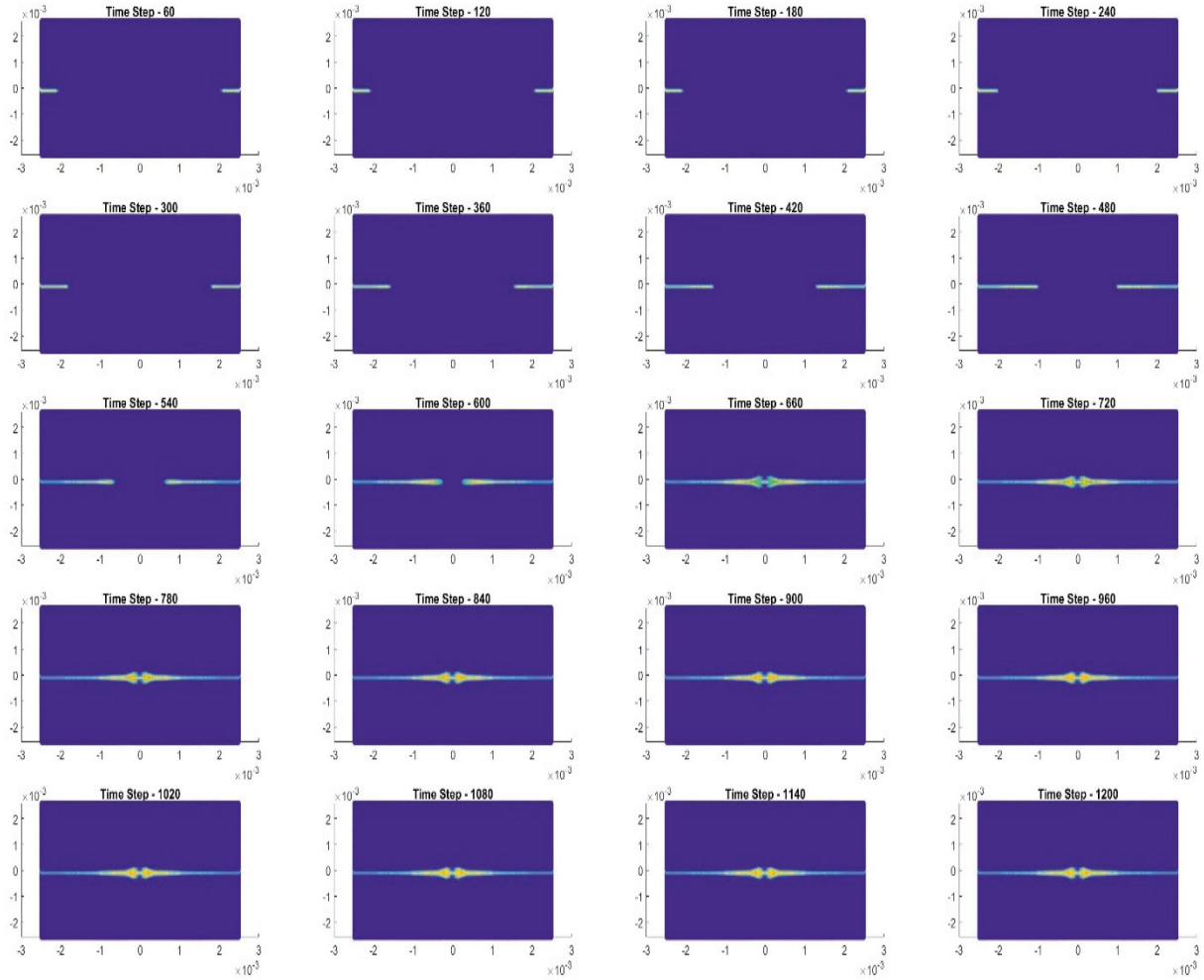

Figure 5: Crack propagation in polycrystalline silicon with GBC 1.0, total time = 2.4 μs and time step 2 ns. Average grain size is 333 μm, with horizon diameter 50 μm

From the observation in figure 5, the crack propagation has a transgranular pattern, where the crack propagates through the grains.

4.2. Case 2 – Polycrystalline silicon – by considering microstructure

In case 2, the sample plate shown in figure 4 is modelled by considering the microstructure, i.e., grains with average grain size of 333 μm according to polycrystalline silicon grain size. Mechanical behaviour of polycrystal material varies from the monocrystalline material due to the presence of grains, grain size, grain boundary conditions, orientations, etc. Therefore, for this simulation the GBC is taken as 0.5, meaning that the bond strength between the two grains is weaker than the bond within the grains itself.

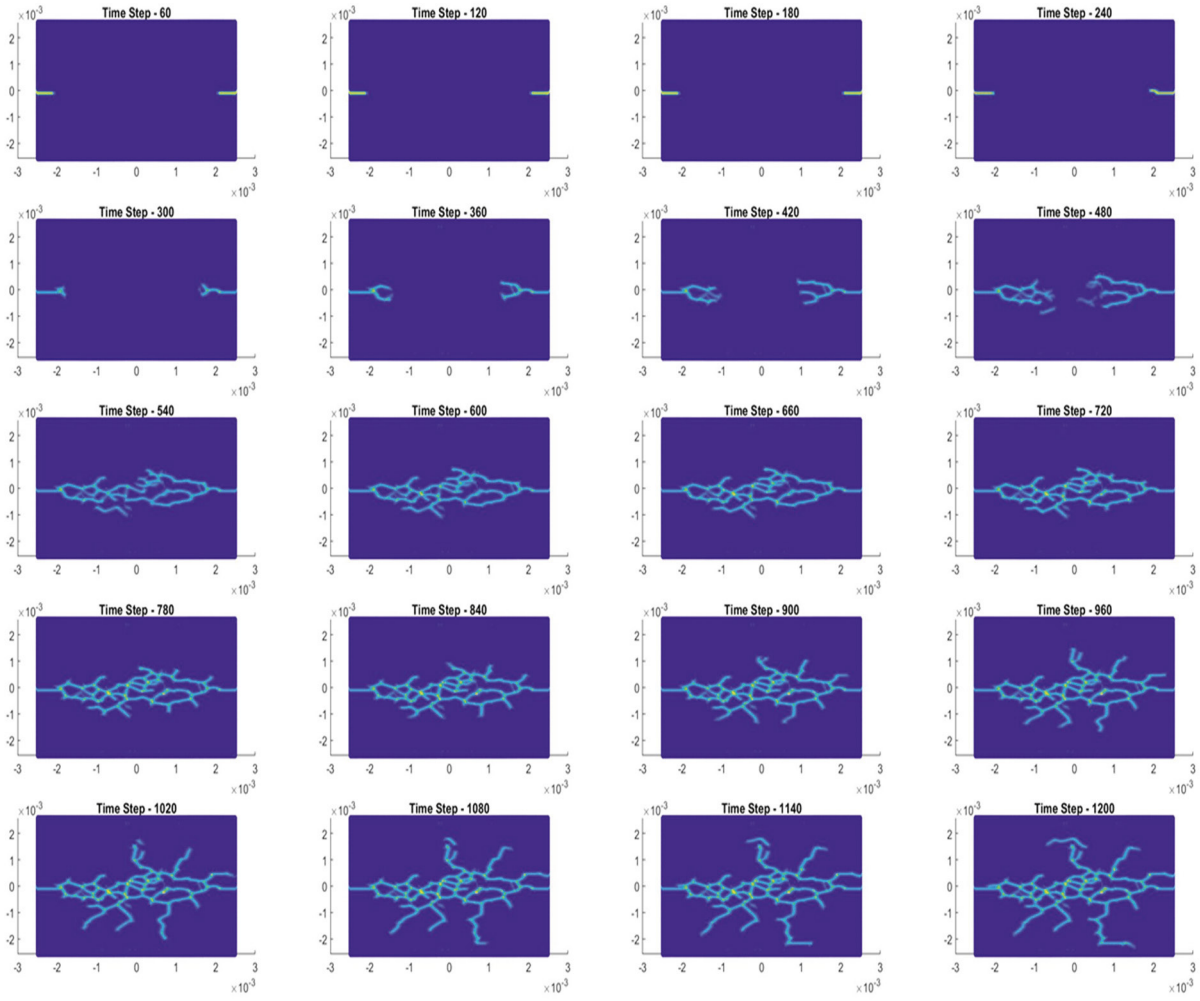

Figure 6: Crack propagation in polycrystalline silicon with GBC 0.5, total time = 2.4 μs and time step 2 ns. Average grain size is 333 μm, with horizon diameter 50 μm

From the observation in figure 6, the cracks initiate symmetrically from the predefined notch on left and right edges. Then the crack propagate through the grain boundaries without damaging the grains. As the crack propagates further, the grains are disconnected from the neighbours and isolated.

The isolating phenomenon in polycrystalline PV cells causes inactive zones, which is also known as degradation of PV cells. Inactive zones are the region where there is no photo-electric effect take place.

4.3. Case 3 – Polycrystalline silicon – GBC 2.0

In Case 3, in a polycrystalline material, the GB bond (i.e., bond between two neighbouring grains) has higher strength than the grains themselves. Therefore, for this numerical case, GBC is considered as 2.0 meaning that the bond strength of GB is higher than the grains themselves.

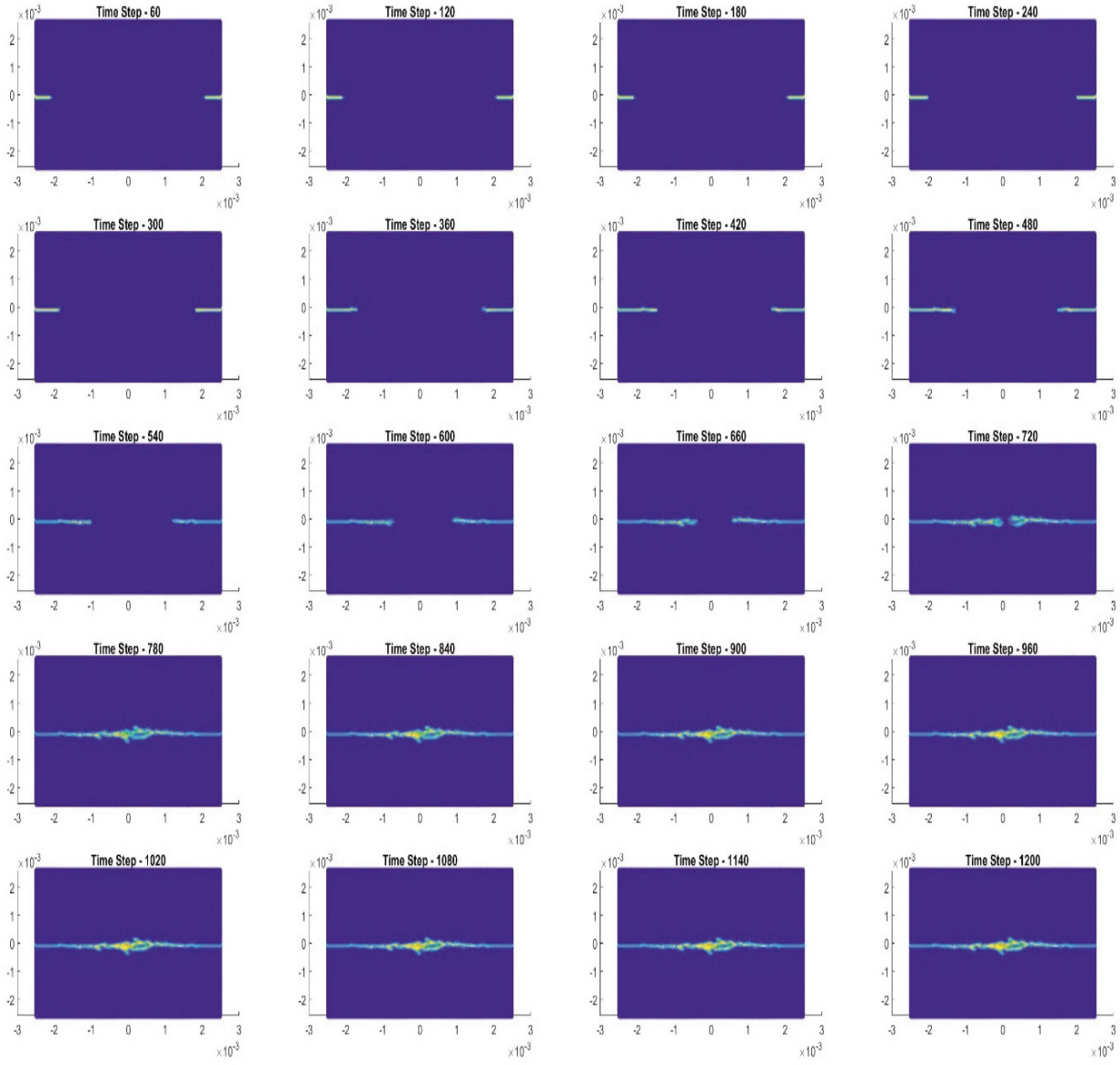

Figure 7: Crack propagation in polycrystalline silicon with GBC 2.0, total time = 2.4 μs and time step 2 ns. Average grain size is 333 μm, with horizon diameter 50 μm

From the observation in figure 7, the crack propagates in a transgranular pattern, where the crack breaks the grains and travels through it.

5. COMPARATIVE STUDY

5.1. Comparison over Grain sizes

A comparative study was carried out in nine simulations by fixing the horizon diameter as 100 μm, where the grain sizes are ranging at 333 μm, 416 μm and 714 μm. As shown in figure 8, the grain size has significant influence on crack propagation behaviour for weak grain boundary cases, i.e., GBC = 0.5 whereas for same or stronger grain boundaries, the influence of grain size on crack propagation is insignificant.

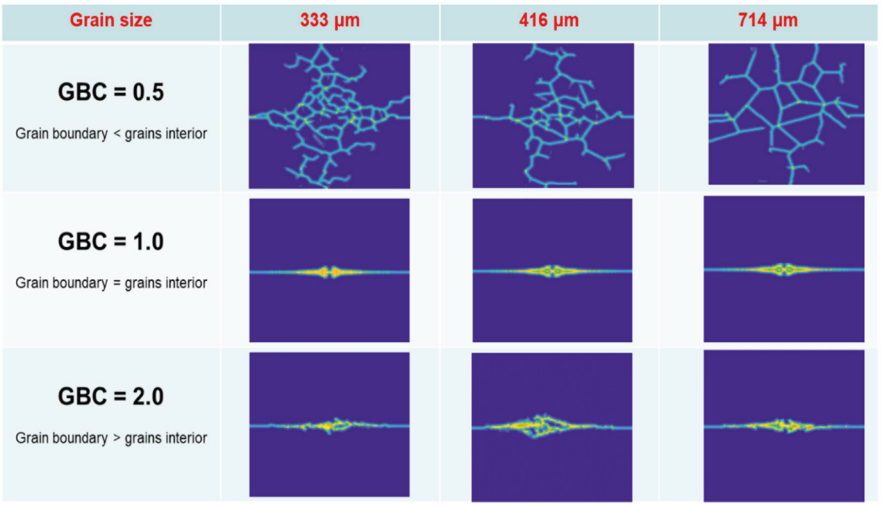

Figure 8: Effect of crack propagation is compared over grains sizes (333 μm, 416 μm and 714 μm) with GBC (0.5, 1.0 and 2.0)

5.2. Comparison over Horizon Sizes

Another comparative study was carried out in nine simulations by fixing the grain size as 333 μm, where the horizon diameter ranging at 202.7 μm, 100 μm and 50 μm. As shown in figure 9, crack patterns become similar as the horizon size decreases for all GBC values.

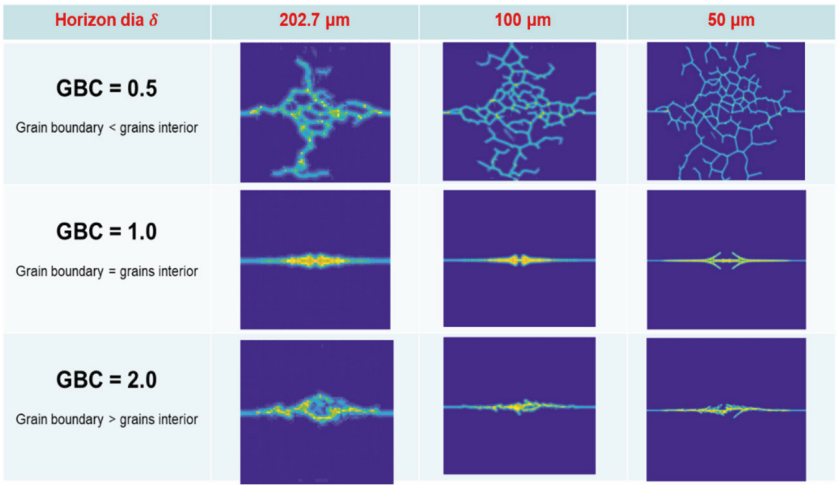

Figure 9: Effect of crack propagation is compared over horizon diameter (202.7 μm, 100 μm and 50 μm) with GBC (0.5, 1.0 and 2.0)

6. CONCLUSIONS

In this study, the peridynamic results of the crack propagation in polycrystalline PV cells, were presented by considering the effect of microstructures (grains). It was observed that microstructure can have significant influence on the fracture behaviour of polycrystalline PV cells if the strength of the bonds crossing the grain boundaries is weak. Grain size is also influential for fracture behaviour for weak grain boundary cases. According to the numerical results, it can be concluded that determining the crack growth in PV panels would be helpful to predict the life span of the PV panels. Moreover, simulation results can be useful to determine the degradation rate of the PV panels.

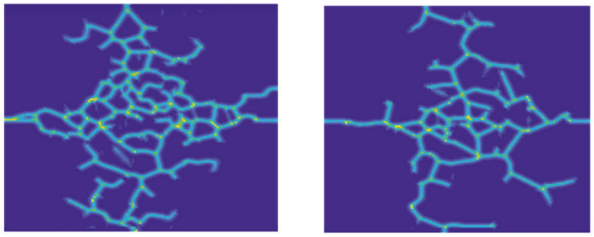

Figure 10: PD crack propagation is similar to the PV cells degradation causing inactive zones

Developed peridynamic numeric framework can be used in future to investigate the mechanical behaviour of PV panels in different environmental and loading conditions.

Acknowledgement

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Nomenclature

PV	Photovoltaics
MW	Megawatt
DC	Direct current
AC	Alternate current
CCM	Classical continuum mechanics
GB	Grain Boundary
GBC	Grain Boundary co-efficient
GI	Grains inside the region
FEA	Finite Element Analysis
FE	Finite Element
2-D	Two Dimension
Al	Aluminium

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