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Image analysis of polycrystalline solar cells and modelling of intergranular and transgranular cracking

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Abstract

An innovative image analysis technique is proposed to process real solar cell pictures, identify grains and grain boundaries in polycrystalline silicon, and finally generate finite element meshes. Using a modified intrinsic cohesive zone model approach to avoid mesh dependency, nonlinear finite element simulations show how grain boundaries and silicon bulk properties influence the crack pattern. Numerical results demonstrate a prevalence of transgranular over intergranular cracking for similar interface fracture properties of grains and grain boundaries, in general agreement with the experimental observation.

Keywords: Photovoltaics; Image analysis; Nonlinear fracture mechanics; Finite element method; Polycrystalline silicon

1. Introduction

Photovoltaics (PVs) based on silicon semiconductors is the most growing technology in the World for renewable, sustainable, non-polluting, widely available clean energy sources. Commercial PV modules are composite laminates with very different layer thicknesses. Thin silicon cells are usually embedded in an encapsulating polymer layer (EVA) covered by a much thicker tempered glass[1] (see Fig. 1(a)). In other cases, symmetric glass-polymer-silicon-polymer-glass laminates are used, especially for semi-transparent facades (see Fig. 1(b)).

The majority of solar cells available on the market are made of either monocrystalline or polycrystalline silicon. Solar cells are separated in their plane by a variable content of EVA, depending on the amount of shading requested. Two main semiconductors, called *busbars*, electrically connect the cells in series. Very thin aluminium conductors perpendicular to the busbars, called *fingers*, are also present to collect the electrons originated by the photovoltaic effect from the surface of the cells to the busbars (see Fig. 2).

The quality control of these composites is of primary concern from the industrial point of view. On the one hand, the aim is to develop new manufacturing processes able to reduce the number of cells or modules rejected. On the other hand, even if all the damaged cells are theoretically discarded during manufacturing, it is impossible to avoid the occurrence of microcracking during the subsequent stages. Sources of damage in silicon cells are transport, installation and use (in particular impacts, vibrations, snow loads and environmental ageing caused by temperature and relative humidity variations).[2–4] Since microcracking can lead to large electrically disconnected areas, there is an urgent need to understand the origin of this phenomenon and find new technical solutions to improve the durability of PV modules.

To investigate the effect of mechanical loads on cracking in solar cells, mini-modules of 10 cells disposed along two rows (5 cells per row) have been subjected to 4-point bending in Ref. 5 (see Fig. 3(a)). The force–displacement curve obtained from this test is depicted in Fig. 3(b) and shows brittle failure as soon as cracking propagates. Microcrack patterns, impossible to be detected by a naked-eye inspection of the cells, were monitored by using the electroluminescence (EL) technique, see Fig. 4.[5] These images refer to the portion of the module span where the bending moment is constant. Cracks develop along some preferential lines almost parallel to the direction of line loading. In case of horizontal busbars perpendicular to the line of loading, Fig. 4(a), a diffuse crack pattern is observed with the appearance of crack branching. For vertical busbars parallel to the line of loading, Fig. 4(b), single cracks propagate and lead to large electrically disconnected black areas. The orientation

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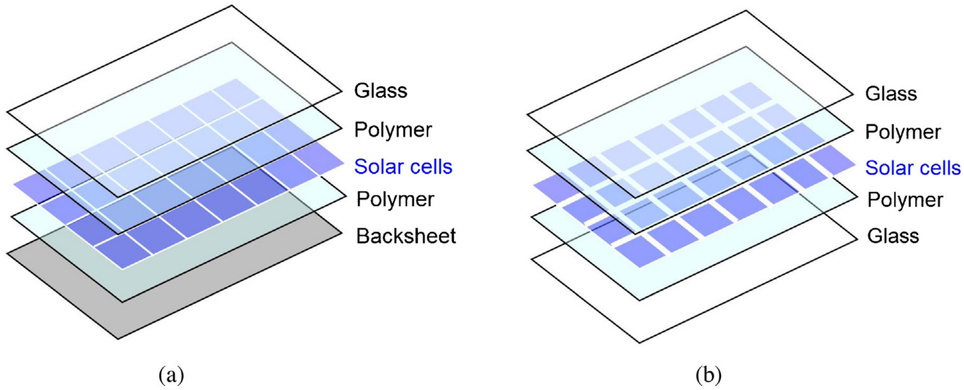

Fig. 1. Two typical stacks of PV modules: (a) PV module for roofs or for solar fields; (b) PV module for semi-transparent roofs or facades.

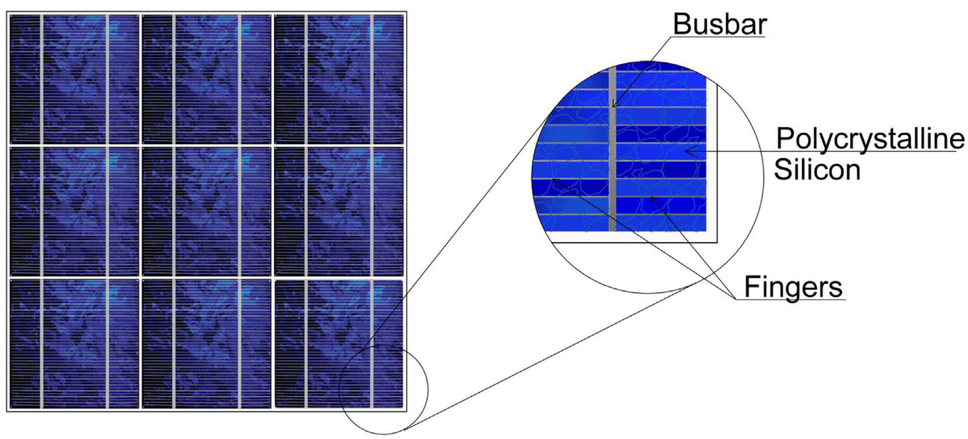

Fig. 2. Sketch of a PV module and detail of busbars and fingers over the silicon cell.

of busbars and of the thin electric fingers with respect to the direction of application of loading has therefore a role on the crack pattern at failure.[5] Both transgranular and intergranular cracks are clearly present and should be considered in numerical models, although a qualitative visual inspection of Fig. 4 would suggest that transgranular cracking is more frequent than the intergranular one.

From the modelling point of view, a multi-physics and multi-scale computational model has been proposed in Ref. 6. The original idea is to couple elastic, thermal and electric fields to achieve a predictive stage in the numerical simulations. To simulate fracture in solar cells of a commercial PV module, structural analysis has been performed by using the finite element method and by considering the laminate as a multi-layered plate. The computed in-plane displacements at the boundaries of the cells were transferred to the micro-models of the individual cells, where the actual material microstructure was considered. In Ref. 6, intergranular cracking was considered as the only possible source of damage. Further progress has been presented in Refs. 7, 8, where coupling between the elastic and the thermal fields has been accounted for by developing a specific thermo-elastic Cohesive Zone Model (CZM).

In the present study, transgranular cracking, i.e., cracking through the grains, is also considered in addition to the

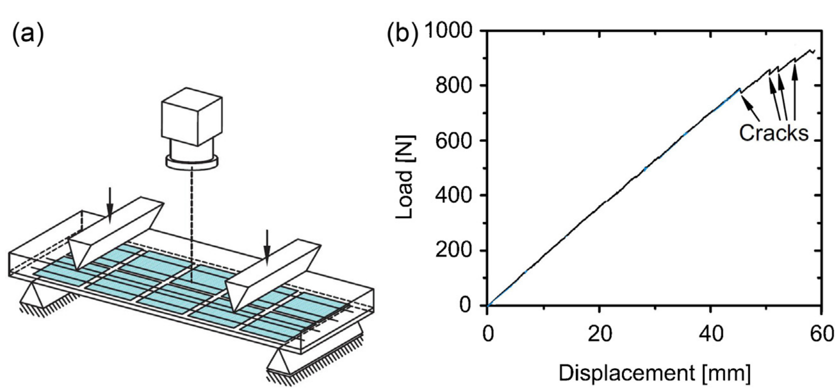

Fig. 3. Setup of the experimental test on mini-modules carried out in Ref. 5 (a) and obtained load–displacement curve (b) (adapted from Ref. 5).