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PEEL TESTING OF RIBBONS ON SOLAR CELLS AT DIFFERENT ANGLES: CONSISTENT COMPARISON BY USING ADHESIVE FRACTURE ENERGIES

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ABSTRACT: The peel test is a very simple and fast method to determine the adhesion of interconnector ribbons to solar cell metallizations. It is part of the solar cell standard DIN EN 50461 and is, due to its ease of use, widely accepted to qualify cell metallizations and the soldering process. In the standard a minimum force of 1 N per mm of joint width is specified but other relevant quantities are missing, for example the peeling angle. We show that this lack of specification influences the peel testing results. We therefore apply the mechanical theory of Kinloch and Kawashita [1,2] where measured peel forces are translated into adhesive fracture energies G_A. The fracture energy is a geometry-independent parameter that describes the energy to break the interfacial bondings at the peel front. It incorporates the dimensions of the ribbon and its stress-strain-curve. We perform 121 peel experiments at 45°, 90°, 135° and 180° of ribbons on continuous front side busbars of cells from one stringing batch. We measure very high forces at 45° (mean value 9.74 N), while the mean values are in the range of 3 N for 90° (3.14 N), 135° (2.46 N) and 180° (3.49 N). The force level at 45° is thus a factor of 4 higher compared to 90°, 135° and 180°. Transforming the force values into adhesive fracture energies, the mean values deviate only by a factor of 0.6 (45°: 510 J/m^2, 90°: 395 J/m^2, 135°: 441 J/m^2, 595 J/m^2). This indicates that the method improves the interpretation of peel testing data by using the adhesive fracture energies as mechanical material parameters to quantify the adhesion.

Keywords: PV module, solder joint, peel test, adhesion, cell metallization, ribbon

1 INTRODUCTION

The first test to qualify the interconnection of crystalline silicon solar cells after soldering is the peel test. The interconnector ribbons are peeled off from the solar cell measuring the force. This easy and fast method is used to accept or reject new cells in a module production line and to optimize the soldering process of a tabber stringer. Although the test is part of the standard DIN EN 50461, various configurations of the test are possible. The weakness of the peel test in terms of consistent testing procedures and equipment is addressed by Klengel and Wendt [3-5]. Their solution is a peel testing machine designed for peel testing solar ribbons where the ribbon is held down at 90° by a low-wear material to avoid cell cracking. However, the use of different peel testing devices and non-identical testing procedures in the PV industry has led to a variety of individual requirements concerning minimum force thresholds or desired fracture patterns.

Here, we focus on the mechanics of the peel test itself. We investigate the impact of the peeling angle to the measured forces and propose the method of Kinloch [1] and Kawashita [2] to determine adhesive fracture energies to quantify the adhesion of the ribbon to the cell.

2 EXPERIMENTAL

2.1 Sample Preparation

For the peel experiments we use standard multicrystalline solar cells with three continuous busbars. The cells are soldered to a 160 µm x 1.6 mm copper ribbon with SnPbAg-coating in a commercially available tabber stringer. The soldering method is infrared soldering. The strings are cut into single soldered cells to obtain 40 solar cells. The rear side of the each cell is attached to a rigid substrate to avoid cell cracking at high peel forces.

In order to translate the peel forces into adhesive fracture energies, the method requires the input of the stress-strain-relation of the ribbon.

To characterize the mechanical properties of the ribbon we use the same SnPbAg-coated ribbon material.

2.2 Measurements

We perform 5 tensile tests on unsoldered copper ribbons until fracture on a Zwick tensile testing machine. As an example, one of these stress-strain curves is shown in Fig.1. Due to the large strains the true stress is computed from the engineering stress.

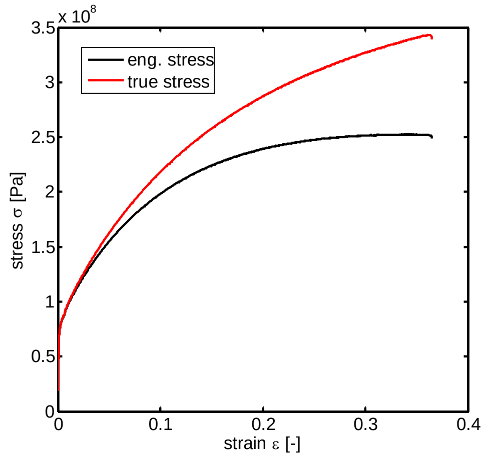

Figure 1: Measured stress-strain-curve of the unsoldered ribbon in tensile mode.

We perform 36 peel tests at a peel angle of 180°, 15 tests at an angle of 135°, 35 tests at an angle of 90° and 35 tests at an angle of 45°.

3 THEORY

The geometrical configuration of the peel test is shown in Fig 2. Following the work of Kinloch [1] the adhesive fracture energy G_A is derived from an energy balance equation

$$G_A = G_{ext} - G_S - G_T - G_B$$

where G_{ext} is the external energy, G_S is the stored strain energy in the peeling arm, G_T is the dissipated energy by plastic tensile deformation of the peeling arm and G_B is the dissipated energy by plastic bending deformation at the peel front. These energies are determined by

$$G_{ext} = \frac{F}{b}(1 + \varepsilon - \cos\alpha)$$

$$G_S + G_T = h\int_0^{\varepsilon} \sigma \, d\varepsilon$$

where F is the measured force, α the peeling angle as illustrated in Fig. 2, b the width of the peeling arm, ε the strain and σ the stress in the peeling arm. In case of plastic deformation it holds $G_T \neq 0$.

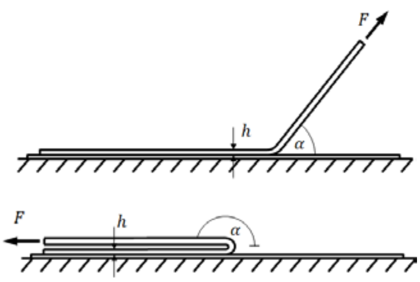

Figure 2: Configuration of the peel test.

The energy dissipated by plastic bending G_B is determined by an iterative method that accounts for the different loading states, such as plastic deformation during bending with elastic deformation during unbending and plastic bending and unbending.

4 RESULTS

Figure 3 shows all 36 peel curves of the 180° tests. In all tests very homogeneous cohesive fracture in the cell metallization is observed and the peel fronts remain in perfect shape without sharp kinks during the tests. For each angle we use every datapoint of every peel curve to create the statistical plot for the measured forces. These data is shown in Fig. 4. We find the peel forces at 45° to be in the range of 8 N to 12 N which is significantly higher than those at 90°, 135° or 180°. Comparing the mean values for each angle, the mean force at 45° (9.74 N) is a factor 4 higher than at 135° (2.46 N).

Applying the method of Kinloch and Kawashita the force values of each peel experiment are transformed into values of the adhesive fracture energy and are shown in Figure 5. The values are on the same level with the largest difference between 90° and 180°. The difference between the mean adhesive fracture energies at 90° (395 J/m^2) and 180° (595 J/m^2) is 200 J/m^2 which corresponds to a factor of 0.66.

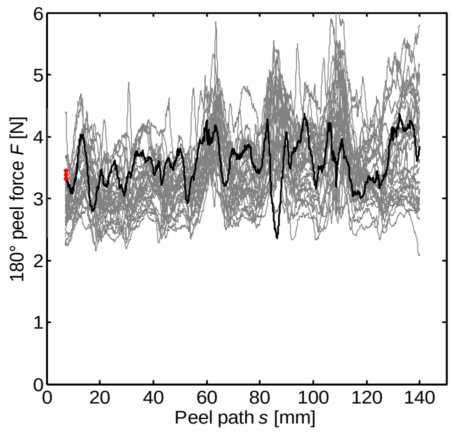

Figure 3: Measured forces of 36 peel tests at 180°. The red marks indicate the machine accuracy.

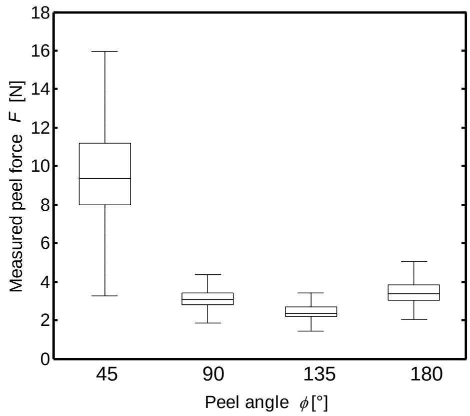

Figure 4: Measured forces of all 121 peel tests grouped by peeling angle.

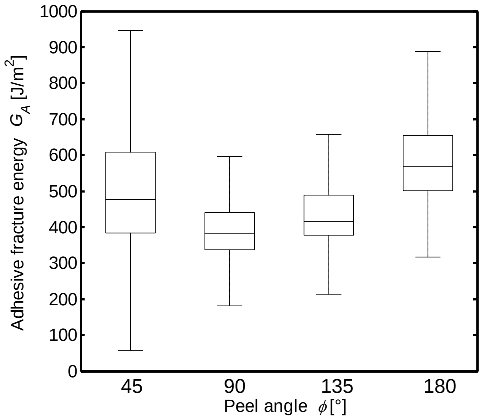

Figure 5: Adhesive fracture energies calculated from peel forces in Fig.4 with the method of Kinloch and Kawashita.

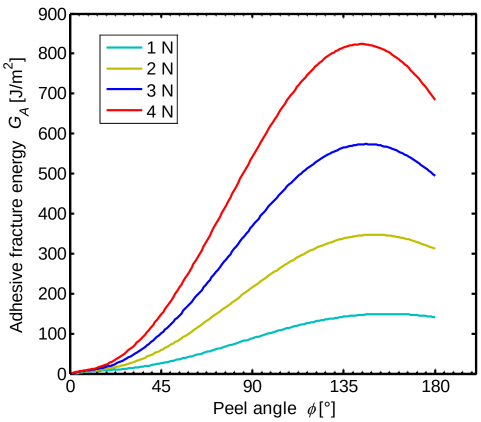

Figure 6: Computed adhesive fracture energies for constant force levels over different peeling angles.

5 CONCLUSION

We apply the adhesive fracture energy method by Kinloch and Kawashita to solar cells and ribbons and can thereby describe the adhesive forces in a solder joint independent of the peeling angle. Assuming constant adhesive fracture energies we find the forces to increase for decreasing angles as shown in Fig.6. Using this information a manufacturer can thus increase or decrease the probability of rejecting novel cell types in his production if his peel test guidelines do not specify the peel angle. We believe this subject to be of major importance for qualifying novel technologies that come along with lower adhesion such as plated contacts or conductive gluing.

As the amount of energy, that is absorbed by plastic bending of the ribbon, depends on the ribbon cross-section, a direct comparison of peel forces for ribbons with different geometries but identical mechanical properties under identical peel testing conditions is not consistent. Again, the use of adhesive fracture energies will allow for a consistent comparison.

6 ACKNOWLEDGEMENTS

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