Cracking of silicon solar cells and solar module transparent cover panels such as glass or polymethylmethacrylate (PMMA) is a major cause of photovoltaic solar module failure in field service. Silicon and cover materials are brittle, and cracking of these materials is expected to result from the extension of pre-existing flaws under stress. Study of the cracking mechanisms is therefore an appropriate area for the application of fracture mechanics principles.

In this study, fracture mechanics techniques were employed to identify the mode of crack propagation, to examine the fracture-initiating flaw, to estimate the nature and magnitude of fracture stress in the field, and to predict analytically the service lifetime. Recommendations for corrective actions are also made.

Fracture Mechanics

Fracture Mode

The displacement of crack surfaces under stress conditions occurs by three basic modes (1) as shown in Figure 1. The elastic stresses and strains produced at the crack tip differ in each mode. Mode I, in which crack surface displacements are perpendicular to the crack plane, tending to open the crack, is called the opening mode. Modes II and III are shearing displacements in the plane of the crack. Mode II is an in-plane shear in which the crack surfaces slide over one another perpendicular to the crack front, whereas mode III produces tearing displacements that slide over one another parallel to the crack front.

Many studies of crack propagation in brittle ceramics have led to the following unique relationship between crack velocity $v$ and crack tip stress intensity factor $K$ for a given material, environment, and temperature (2):

$$v = \alpha K^n$$

where $\alpha$ and $n$ are empirical constants.

The stress intensity factor $K$ is then related to the applied stress $\sigma$ and flaw size $C$ in the form

$$K = \sigma Y \sqrt{C}$$

where $Y$ is a flaw shape factor.

During crack propagation, $K$ increases with increasing values of $C$. When the flaw grows to a critical size $C_{cr}$, the crack tip stress intensity factor at the same time reaches a critical value of $K_{cr}$.

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and fast crack propagation occurs, resulting in fracture. Fracture stress $\sigma_{cr}$ can thus be written from equation 2 as

$$\sigma_{cr} = \frac{K_c}{\sqrt{Y}}$$  (3)

In this equation $K_c$ is called the critical stress intensity factor.

A critical stress intensity factor (i.e., $K_{IC}$, $K_{IIC}$, or $K_{IIIC}$) is associated with each mode of cracking and describes the magnitude of the stresses in the material at the crack tip that produce rapid crack propagation. The above-described crack surface displacement can be used to identify the fracture mode of photovoltaic solar module components. The detailed nature of the cracking may provide information about the nature of the force causing the fracture.

Fracture Mirror

The fracture surface of a brittle material subjected to a constant subcritical load $\sigma$, and then failed by a load greater than $\sigma_{cr}$ is described schematically in Figure 2. In the figure, $a_i$ and $b_i$ represent the radii of the initial flaw depth and length, respectively, while $a_{cr}$ and $b_{cr}$ refer to the depth and length of the critical flaw size.

If the initial flaw in the brittle material does not exceed the critical size at the applied stress level, the material will sustain the first load application. However, during the subsequent load applications and time at load, the flaw will grow in size and may eventually attain the critical size, resulting in catastrophic failure. During the catastrophic fracture, crack extension from the critical flaw appears to be accelerated in the mirror region under applied stress. The velocity of crack propagation increases with the extension of the crack until reaching the velocity of sonic waves; at that point it encounters increasing interference and branchings, resulting in hackles (3) (see Figure 2).

The critical flaw may not always be seen on the fracture surface of a ceramic material under subcritical loading. However, the critical flaw size can be calculated from equation 3 if the failure stress is known. In this case, $C_{cr}$ can be rewritten as

$$C_{cr} = \left[ \left( \frac{2^2}{K_{IC}} \right) \left( \frac{1.2\pi}{\sqrt{Y}} \right) \right]$$  (4)

where $C_{cr} = \sqrt{a_{cr} b_{cr}}$ = critical flaw size

$$\phi = \text{flaw geometric factor} = \sqrt{1.2\pi / Y}$$

$K_{IC}$ = fracture toughness of material

For rapid loading of brittle materials, the critical flaw size is equal to the initial flaw size because of lack of time for subcritical crack growth.

It has been extensively demonstrated that the product of fracture stress, $\sigma_{cr}$ and the square root of the mirror radius $r$ is constant in glass (4, 5) and ceramics (6):

$$\sigma_{cr} r^{1/2} = A$$  (5)

where $A$ is commonly referred to as the mirror constant, which is a material constant relating to the fracture toughness of the material. However, the value of $A$ is also dependent on the nominal stress (macrostress) states of the sample under different loadings (5). For example, in soda-lime glass samples tested in air at room temperature $A = 1.72 \pm 0.28$ MN/m$^{3/2}$ for a tensile test and $A = 2.74 \pm 0.15$ MN/m$^{3/2}$ for a four-point bending test (5). The fracture stress of a component can thus be calculated by measuring the fracture mirror radius if the "A" value is available.

Subcritical Crack Growth

The existence of time-dependent failure in brittle materials due to subcritical crack growth has been well documented (6, 7). This phenomenon is usually attributed to stress corrosion at the crack tip due to moisture in the environment. Fractographic analysis of time-dependent failure in soda-lime glass (7) revealed that the ratio of fracture mirror to critical flaw size is a constant, independent of strain rate, whereas the ratio of mirror to initial flaw size varies with time under load. In other words, the fracture-mirror constants determined in rapid failure and in delayed failure are identical, because once the critical flaw size is reached, the processes leading to mirror formation are the same.

From equation 1, using $\frac{dc}{dt}$ = $v$, the following equation, which relates the time-to-failure under a constant stress to the initial flaw size and the fracture mirror size was derived (7):

$$\frac{t}{C_{cr}} = \left[ \left( \frac{1.2\pi}{\phi} \right)^{m} \left( \frac{v/C_{i}}{A^n/a_n^c(1/n - 1)} \right)^{n/2} \right]$$  (6)
where \( t = \text{time-to-failure} \)

\[
C_i = \text{initial flaw size}, C_i = \sqrt{a_i b_i}
\]

\( n \) and \( \alpha \) = empirical constants from equation 1.

In the case of soda-lime glass tested in air (6) the following results were reported:

\( n = 15.8 \)
\( \alpha = 0.045 \)

and \( \phi \) = flaw shape factor

- 1.42 (semi-elliptical)
- 1.57 (semicircular)

Substituting these values in equation 3, the time-to-failure under loading may be determined as a function of ratio of mirror radius to flaw size. Conversely, with a known applied stress, the maximum allowable flaw size for a required lifetime may be determined. With PMMA and Si, values for \( n \) and \( \alpha \) are not yet available.

APPLICATION EXAMPLES

The examples illustrating the use of these techniques cannot be treated in detail as a result of space limitations; only the problems and conclusions will be presented here. Detailed analyses are presented elsewhere (8).

Fracture of Glass Superstrates

Glass modules* were found to be cracking after four weeks in field service, as shown in Figure 3. Analysis of these failures indicated that the fracture resulted from a flaw existing at the time of module assembly which propagated under primarily tensile stress. The fractured surfaces is shown in Figure 4. The flaw size was 1000 microns (-0.040 inches) and the stress for failure was 15.3 MN/m² or 2.2 ksi. The lifetime was calculated to be a few seconds. Using this failure stress as an indication of those encountered in the field, the maximum flaw size for these glass panels must be less than approximately 60 microns to achieve the required 20-year lifetime.

Fracture of Polymethylmethacrylate (PMMA) Superstrates and Substrates

Fracture of a module** with PMMA superstrate and substrate after a standard qualification test*** is shown in Figure 5. Similar analysis indicated that tensile stresses resulting from thermal expansion mismatch during negative temperature cycles was the cause of failure. At present insufficient data are available on the behavior of PMMA to predict fracture stresses or requirements for lifetime.

Silicon Solar Cells

A typical failure (Figure 6) was observed to result from a solder droplet, which produced stresses on a flaw approximately 70 microns deep at the wafer edge. More fundamental property information will be required to predict stress and lifetime. However, the magnitude of the flaw (70 microns) is less than that which is usually cause for rejection of a wafer in quality control.

** United Energy Corporation, Honolulu, Hawaii. (Model 1212)
***fifty cycles from -40 to 90°C at 100°C per hour rates.

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* Spectrolab Solar Modules Block II at Natural Bridges National Monument, Utah.
CONCLUSIONS

The following conclusions can be drawn from the above discussion:

1. The tools of fracture mechanics exist by which to predict the relationship between surface damage, fracture strength, and lifetime to fracture for the brittle materials used in photovoltaic modules.

2. Application of these tools to failures provides useful information in defining quality limits on allowable damage to components.

3. Additional data are needed for some materials (e.g. silicon) in order to complete the analysis.

REFERENCES


