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Normal impact of sand particles with solar panel glass surfaces

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ABSTRACT

An analytical elasto-plastic model coupled with a transient impact model is developed to study single normal impact of small sand particles on solar panels glass surfaces. Nanoindentation measurements are performed on two commercial photovoltaic protective glasses, namely annealed and tempered, to extract their mechanical properties required for the impact model. The model is qualitatively validated through sandblasting experiments. Evaluation of the impacting sites using scanning electron microscopy shows significant plastic impressions of Vickers-like indentation for small sand particle impact. Employing the analytical model, parametric study is performed to examine the glass deformation due to single sand impact using different corner radii, impact speeds and glass types. The proposed model is used to predict plastic damage due to normal sand impact.

1. Introduction

With significant growth of solar energy harvesting as a clean and renewable source of energy, more attention is now being paid on the efficiency of solar power converters. Two of the most highly used technologies for converting solar radiation to electricity are photovoltaic (PV) solar panels and concentrated solar power (CSP). To maintain the efficiency for both systems, a crucial part is the protective outer surface typically made of transparent glass. Glass has been used extensively in many applications such as construction, decoration, medicine and more recently automotive, aerospace, optoelectronics and solar energy harvesting. The most important properties of glass, which has given rise to its broad application, are its high optical transparency while giving reliable protection. The high transparency of glass makes it possible to protect the surface of solar cells from harsh environments while delivering high solar radiation to solar cells in PV panels or reflective surfaces of CSP glass mirrors. Notwithstanding the recent progress in solar energy converters, their efficiency is still low, especially for PV solar cells (less than 20%) [1–3]. Therefore, it is desirable to deliver the highest possible percentage of sunrays received by the outer surface to the inner layers, i.e. full transparency. Accordingly, any phenomenon that interferes with light transmission is highly undesirable.

The best efficiency of solar panels is achievable in areas with abundant solar energy. The Middle East and North Africa (MENA) as well as southwest of the United States are examples of the best areas to harvest solar energy [4]. However, the sunniest areas are generally the dustiest; covered by deserts where sandstorms are frequent. Besides the accumulation of dust, which could affect the efficiency up to 40% [2,5], the permanent damage due to the sand impact is another considerable efficiency drag for PV solar panels as well as CSP in such environments [6,7]. Indeed, solar panel surfaces are inevitably exposed to various degradation mechanisms including chemical degradation and mechanical damage, which in turn can impair the transparency of the protective surface of PV panels and reflectivity of glass mirrors of CSP.

The mechanical damage is mainly caused by sand-surface interaction (sand impact). The average wind speeds in some parts of the Middle East can easily reach up to 15 m/s [7–9]. This is enough to move particles in the diameter range of 120–500 μm at the ground level where solar panels are installed and furthermore, they can also force particles smaller than 120 μm diameter to rise into the atmosphere [6]. It has been shown that not only does sand impact affect the mechanical resistance of the surface and its durability, but it can also lead to optical transmission loss via formation of local deformations and cracks that reduce light transmittance [5]. Two damage mechanisms are a result of sand impact: ductile yielding and brittle cracking, which are usually controlled by particle size and shape [5,10,11]. Ductile yielding leaves plastic impression while brittle fracture causes micro cracks and subsequent propagation of lateral cracks. For small particles

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Nomenclature

a_H	Hertzian half contact width, m
A_c	Contact area, m^2
A'	Truncated contact area, m^2
A_{res}	Residual area, m^2
c	Constant relating maximum Hertzian pressure to yield strength at onset of yielding ($c = 1.08$ using von Mises criterion)
E	Modulus of elasticity, GPa
E^*	Reduced modulus of elasticity, $E^* = (\frac{1-{\nu_1}^2}{E_1} + \frac{1-{\nu_2}^2}{E_2})^{-1}$, GPa
F	Normal contact load, N
F_Y	Contact load at the yielding inception, N, $\frac{9\pi^3}{16} c^3 \sigma_Y R^2 \left(\frac{E*}{\sigma_Y}\right)^{-2}$
H	Material hardness, GPa
h_c	Contact depth, m
h_a	Spherical–conical transition depth, m, $(r - r\sin\theta)$
h_o	Distance between indenter tip apex and cone theoretical apex depth, m, $\left(\frac{r}{\sin\theta} - r\right)$
m	Particle mass, Kg
p_m	Mean contact pressure, GPa
p_H	Maximum Hertzian pressure, GPa
R	Sphere radius, m
r	Indenter radius, m
R_c	Particle corner radius, m
r'	Truncated contact radius, m
S	Stiffness, N/m
V_o	Initial particle speed normal to the impacted surface, m/s
ν	Poisson's ratio
δ	Penetration depth, m
δ_Y	Penetration depth at the inception of yielding, m, $\frac{9\pi^2}{16} c^2 R(\frac{E*}{\sigma_Y})^{-2}$
σ_Y	Yield Stress, GPa
$\dot{\delta}$	Particle speed during impact, m/s
$\ddot{\delta}$	Particle acceleration during impact, m/s^2

with sharp edges, ductile yielding is the predominant form of damage [11] while for larger particles, local ductile yielding is followed by prevailing lateral and radial cracks [5].

The use of glass as a protective cover for solar panels is well established [5,7,12] and hence, numerous experimental studies such as sand blasting have focused on glass as the target for impact. In particular, some studies have been performed on impact damage of solar panels by investigating the outer surface under laboratory conditions with normalized sand [12,13] or with sand collected randomly from the field [5,6,14–16]. Ludwig and Stoner carried out a quantitative study on the abrasion resistance of surfaces in optical devices by falling abrasive sand. They have also provided empirical models for understanding the abrasion phenomenon using their experimental results [17]. Bousbaa et al. [18] investigated the effect of sandblasting duration on the mechanical properties as well as the optical performance of glass in a sandblast simulator. They showed that the optical and mechanical properties of glass dropped significantly after 90 min of exposure to sand impact. In another study by the same group [5], the effect of sandblasting using sand particles ranging from 100 μm to 800 μm was investigated for different impact angles and time durations. Significant drop in optical transmittance (up to 36%) was reported after sufficient amount of sandblasting time (70 min) and especially, for normal impacts. Marouani et al. studied the effect of collisions of different sand sizes on the optical performance of PV Cells [19]. They used large sand particles and observed a noticeable drop in optical performance of the PV panels. The loss in optical performance was attributed to the diffusion of light at impact locations.

Owing to the random nature of sand impact (characterized by wide range of grain size, shape, materials, velocities, and densities), it is a very complex phenomenon to model [7]. This explains the significant dominance of experimental approaches in the literature and paucity of analytical/numerical models. Yet, since impact damage is a successive process, recording multiple impacts in an experimental test, is impossible [12]. It is even more complicated when dealing with sand impact during sandstorms as other parameters with inherent statistical distribution such as particle size, geometry, impact velocity, and sand density play key roles. It is therefore desirable to develop analytical/numerical models, which can potentially overcome the difficulties associated with experimental measurements. Numerical/analytical studies reported in the literature on the impact between particles and transparent surfaces chiefly involve the impact of a highly rigid substance (mostly metallic particles) and brittle glass sheets [12,20–26]. To the best of the authors' knowledge, no analytical study has been done specifically on small sand particle impact with the protective surface of solar panels considering various characteristics of the sand. This is addressed in the current study. Yet it should be noted that the focus is on surface indentation (plastic impression) damage mechanism as the beginning step, and multiple impacts will be addressed in a future study.

Herein, the proposed impact model uses an analytical elasto-plastic indentation approach developed by Li and Komvopoulos [27] along with a transient impact model to calculate contact parameters during and after single sand impact. The validity of the approach is examined through sandblasting experiments with small sand sizes and subsequent evaluation of the impacting site using scanning electron microscopy (SEM). The numerical results are verified against a finite element (FE) model of transient normal impact. Upon validation and verification, a parametric study is carried out for different impact conditions such as impact velocities, corner radii and glass types. Although, this paper primary focus is on the impact of sand particles with solar surface glass, the approach can be used for any elasto-plastic spherical impact. It is worth mentioning that there is no experimental/analytical report in the open literature to investigate the sand particle parameters and how they influence the behavior of solar glasses under impact. Therefore, as a first step, single normal impact of sand particles with two commercially used solar glasses (namely, annealed and tempered) is modeled and a parametric study is performed to study the influence of different parameters on the behavior of abovementioned glasses in the plastic deformation regime.

2. Glass indentation experiments

Solite, typically used in the solar PV industry for outer surface protection, is considered as the material under investigation. It is a low iron glass manufactured by rolling and formed with a stippled or textured diamond pattern on one side to increases light trapping [28]. It poses 90% and 91% optical transmission and it is typically available as annealed and tempered. Both glass types used in this study are from Torstenson Glass Company. Table 1 shows the chemical composition of solite glass.