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Surface reliability of annealed and tempered solar protective glasses: Indentation and scratch behavior

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ABSTRACT

Solar glass is exposed to mechanical contact cleaning and sand particle impact during operation in outdoor environments resulting in optical efficiency loss as well as decrease in mechanical integrity, durability and reliability. The current study investigates the mechanical behavior of two different solar surface glasses through a series of low and high load indentation and scratch experiments. Nanoindentation experiments are performed on the glass substrate in order to measure the hardness and elasticity moduli at different depths below the surface. Scratch experiments are also preformed to find the critical load for the extent of plastic zone or the onset of micro-cracking. The influence of heat treatment for photovoltaic glasses on mechanical properties such as elastic modulus and hardness, and surface properties such as friction coefficient and elastic recovery is examined in this study in which heat treatment is found to affect both mechanical and surface properties. Also, different resistance behavior is observed in low and high load experiments as well as in indentation vs. scratch experiments.

1. Introduction

Glass has been used widely in various applications such as construction and decoration, medicine, automotive, aerospace, optoelectronics and solar energy harvesting (Burrows and Fthenakis, 2015; Lampert, 2003). In particular, owing to its superior optical transmission, it is an essential part of solar panels protecting solar cells while delivering high solar radiation to the substrate. Due to growing demands for cleaner energy, researchers have focused on solar energy convectors and especially their efficiency. Despite significant improvements in solar panel technologies, their efficiency is still low (around 20%). To sustain and further improve this efficiency, maximum optical transmission through the protective glass is necessary for the service life of the cell (Mani and Pillai, 2010). This specifically is critical in harsh environments with dusty weather conditions and frequent sand storms, which interestingly happen to be the sunniest areas of the world attracting many solar industries and renewable energy agencies. In fact, accumulation of dust as well as the permanent damage due to sand impact or other contact loads (e.g., mechanical cleaning) are the most important efficiency drags for photovoltaic (PV) as well as concentrate solar power (CSP) panels in these regions (Karim et al., 2014, 2015; Sarver et al., 2013). In fact, sand impact and other surface damage not only affect the mechanical resistance of the surface and its durability, but can also lead to early optical transmission loss via local deformations, scratches and cracks (Bouaouadja et al., 2000; Bousbaa et al., 2009; Bouzid and Bouaouadja, 2000; Wiesinger et al., 2016). Thus, good mechanical integrity and reliability are critical for solar panel protective glasses to prevent such detrimental effects.

Key factors influencing the mechanical properties of glass are its chemical composition and processing techniques. Through these factors, it is possible to manufacture glass with unique advantageous characteristics necessary for specific applications e.g., solar energy harvesting. In fact, the processing techniques throughout different stages of fabrication significantly alter the mechanical behavior of glass. Quantifying the effect of these processes on the mechanical behavior of glasses is of tremendous importance to designers and engineers especially in view of utilizing glass for protection against external damaging surface effects.

Instrumented indentation and scratch methods have been extensively employed to characterize the mechanical properties, the extent of deformation and failure mechanisms of different materials such as metals, polymers, glasses as well as different coating materials (Arora et al., 1979; Bandyopadhyay et al., 2012b; Chen et al., 2011; Clark et al., 2014; Humood et al., 2016b; Li et al., 1998; Samadi-Dooki et al., 2016; Schneider et al.,

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2012; Sumitomo et al., 2011; Tandon and Cook, 1993; Tayebi et al., 2004). Indentation methods measure the resistance of a material to permanent plastic deformation. Particularly, nanoindentation is widely utilized to examine the mechanical behavior of glass at the nanoscale. The method provides a measurement of the reduced elastic modulus (E_r) and hardness (H) for glass (Arora et al., 1979; Dey et al., 2011; Kese et al., 2006). Glass hardness is of special importance since it is an assessment of the material resistance to contact damage (Cook and Pharr, 1990). Nano/micro scratch is an effective and complementary method to nanoindentation, providing a measure of friction coefficient, elastic recovery (EL), and material shear stress. Through this approach and by employing scanning electron microscopy (SEM), it is possible to determine the damage zones inside and outside the scratch groove. Previous attempts on the scratch of glass reveal different deformation mechanisms at different depths below the surface due to a varying level of sub-surface shear stress (Bandyopadhyay and Mukhopadhyay, 2013). In addition, due to such shear deformation, mechanical properties including E_r, H and EL inside the scratch grove are 30–60% less than those of the unscratched surface (Bandyopadhyay et al., 2012b).

In regards to protective glasses of solar panels, sand impact and other mechanical contacts have tremendous detrimental effects on the efficiency of solar panels as their contributions to surface deformation and crack nucleation interfering with light transmission. Accordingly, understanding the details of the mechanical and surface behavior of glass is of special importance for predicting the influence of contact loads on glass surface quality. Annealing and tempering are the two most common finishing processes utilized to enhance the resistance to impacts and external loads in solar cell applications (Burrows and Fthenakis, 2015; Dhere and Raravikar, 2001; Taniguchi et al., 1997; Wiesinger et al., 2016). Notwithstanding the abundance of studies on the mechanical behaviors of different glasses (e.g., Bandyopadhyay et al., 2012a; Chorfa et al., 2010; Goodman and Derby, 2011; Schneider et al., 2012), nano/micro mechanical testing of annealed and tempered *Solite* glasses as well as comparison of their behavior and the effectiveness of finishing processes (annealing and tempering) have not been reported in the literature which is very important in view of the use of *Solite* in the solar industry.

In the current study, the influence of heat treatment on surface damage tolerance is investigated for both annealed and tempered commercial *Solite* solar surface glasses using indentation and scratch experiments. A series of low to high load nanoindentation experiments are carried out on the glass substrate to measure the hardness of the substrate as well as its elasticity moduli at different depths from the surface. Moreover, to find the critical load for the onset of micro-cracking as well as the extent of plastic zone, scratch experiments are performed. Subsequently, the influence of heat treatment for PV glasses on the mechanical properties such as elastic modulus and hardness, and surface properties such as friction coefficient and elastic recovery is discussed.

2. Experimental setup

2.1. Materials

The glass under investigation, *Solite*, is a widely used material in the solar industry. It has low iron content and is manufactured by rolling with a textured pattern on one surface side. The texturing captures a portion of the reflected light and enhances light transmission (Solar, n.d.). *Solite* has a chemical composition similar to soda lime glass (see Table 1). According to manufacturer specifications, this type of glass transmits 91% of solar radiation. Solite glass is available commercially in both annealed and tempered conditions, where the differences are from different heat treatments.

Table 1
Chemical composition of *Solite* glass (Solar, n.d.).

Component	Weight%
Silicon dioxide (SiO_2)	73.0
Sodium oxide (NaO)	14.0
Calcium oxide (CaO)	8.7
Magnesium oxide (MgO)	3.9
Other trace elements	0.4

Annealed glass heat treatment is performed by heating the glass to about 500–550 °C followed by slowly cooling the glass to relieve any random (unwanted) internal stresses. For additional tempering process, Solite glass sheets (after being annealed) are heated to about 730 °C, which is close to the softening point of glass (Solar, n.d.). Then, it is cooled in a fast manner (quenched) so that the outer surface and edges are cooled immediately to a rigid surface/edges, while the core is allowed to cool down slower. Due to the constraint of the process, compressive stresses are built up in the surface layer and tension stresses in the inner material. The compressive stress causes any surface flaw to be pressed by the retained compressive forces, while the inner layers remain free of the defects alleviating the crack initiation at the core (AGC, n.d.; Barsom, 1968; Schneider et al., 2012; Tandon and Cook, 1993). Due to the high outlier compressive stress, tempered glass surface is stronger under normal (compressive) deformation. Owing to its simple process, annealed glass is less expensive than tempered glass, however, annealed glass breaks into large sharp shards which raises safety concerns. Residual stresses cause the tempered glass, if broken, to crush into very small chunks instead of breaking into jagged shards as plate glass creates. The granular chunks are less likely to cause an injury and therefore tempered glass is known as safety glass and thus a material of choice for architectural and automobile windows due to safety consideration and regulations (Schneider et al., 2012).

The samples examined here, have dimensions of 25 × 25 × 3 mm and 50 × 50 × 3 mm for the annealed and tempered glass, respectively. The surface topography of both glass samples is obtained by AFM (Fig. 1) where the root mean square (RMS) roughness, denoted by R_q, is measured to be 0.7 and 1.25 nm for tempered and annealed glasses, respectively.

2.2. Nanoindentation measurements

Nanoindentation experiments are conducted using a commercial nanoindenter (TriboIndenter (TI) Premier, Hysitron Inc., Minneapolis, MN). For low load nanoindentation, the 2D nanoindenter transducer with three-plate capacitor is used and is calibrated up to 13 mN indentation force. While for higher loads, a high load transducer, *3D OmniProbe*, is employed for loads up to 150 mN. All experiments are done at room temperature (23 °C) and ambient humidity. The instrument thermal drift is less than 0.1 nm/s for all experiments. For nanomechanical testing, glass samples are cleaned using propanol and then are secured with adhesive on a metal substrate for support. The indentation system also possesses a scanning probe microscopy (SPM) capability and therefore, in-situ surface topography can be measured using a low contact force of 2 μN. A sharp Berkovish (three sided pyramid) probe, with a 150 nm tip radius and total angle of 142.3°, is used for both low and high load indentation measurements.

Nanoindentation provides an indirect measurement of mechanical properties. It measures penetration (contact) depth (h_c) and