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Design and fabrication of freeform glass concentrating mirrors using a high volume thermal slumping process

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ABSTRACT

Concentrated photovoltaics (CPV) power is a form of clean and renewable energy. However, the cost of harvesting solar energy is still economically prohibitive as compared to more traditional electricity generation methods such as hydroelectric or fossil fuel power. In this study, an innovative, high volume but low cost thermal slumping process was proposed as an alternative method for manufacturing of glass mirrors for high concentration photovoltaic system. In this paper, first a freeform optical design was performed to create a two-stage concentrator with $\pm 1^{\circ}$ acceptance angle and uniform output irradiance. Ray-tracing simulation was performed to evaluate the optical design. A machinable ceramic, MACOR®, was tested as mold material for its preferred mechanical and chemical stability at high temperature conditions. To assist the development of the slumping process, finite element method (FEM) simulation was performed to compensate for the mold design for manufacturing errors in this process. Moreover, surface profile and surface roughness were measured to characterize the thermal slumping process. Different manufacturing parameters were tested to identify the proper slumping conditions. It is discovered that surface roughness of the inner surface of the slumped glass mirror remained unchanged after slumping under a pre-determined soaking temperature. This study established a methodology for low cost, high volume glass optics for possible solar concentrator applications.

1. Introduction

Concentrated photovoltaics (CPV) is becoming an alternative approach to production of electricity over the conventional fossil fuel based energy generation approach. Solar photovoltaics can directly generate electricity without creating harmful emission during operation [1]. However, the cost structure of solar energy today is less favorable as compared with more traditional electricity generation methods, such as gas or hydro powered generators. Solar energy tops the energy generation list at 25 to 30 cents per kilowatt-hour, compared with just 3 to 5 cents for coal or hydroelectric [2].

To improve photovoltaics systems' efficiency and reduce manufacturing cost and complexity, different designs were proposed. These designs include different energy conversion methods, optical design, and fabrication and assembly methods [3]. A photovoltaic solar system normally uses two typical designs, i.e., non-concentrated flat plate and concentrated photovoltaics (CPV). Concentrated collectors reduce the total area of photovoltaic receivers by reflecting or refracting the incident light off a large aperture optic onto a small absorbing area.

High concentration of sun light has two main advantages. First, it reduces the numbers or area of photovoltaic cells, and therefore reduces the cost of a solar system because lower number of photovoltaic cells is used. This is especially significant for the new multi-junction III–V photovoltaic cells [4]. Second, it significantly increases the level of light intensity. At a high flux level, electricity generation efficiency of solar cells is drastically improved, again particularly when multi-junction photovoltaic cells are used [5]. Therefore, there is a general agreement that some degree of concentration would be desirable for most solar photovoltaic applications.

However, the cost and complexity associated with optical concentrators may outweigh the potential gains. Therefore, finding a high volume and low cost concentrator manufacturing process is critical to photovoltaic concentrator fabrication, especially the primary mirror fabrication. To fabricate the primary mirrors for high concentration solar systems, injection molding is one of the popular manufacturing methods [6–8]. Hot and roller embossing have also been tested to fabricate Fresnel primary lenses [9]. These methods are cost effective but the polymer optics lack the performance due to the constraints from the polymer materials used.

On the other hand, compared to polymer materials, glasses are more durable, and thus can be used in harsher environments,

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such as in desert condition, or can work at high temperature applications because of their high glass transition temperature (T_g), good chemical stability, and robust mechanical properties [10]. Unfortunately, traditional fabrication methods for glass optical components were expensive, time consuming, and difficult to be adapted for high volume manufacturing. To this end, precision glass thermal slumping process is a possible technique that derives from glass compression molding process and can be adopted for high volume precision glass optical elements fabrication [11]. Recently, precision glass thermal slumping technique has been used to fabricate concentrating mirrors as a high volume, low cost solution [12]. However there are still quite a few unsolved issues with this technology, mainly due to lack of proper understanding about the precision glass forming.

In glass thermal slumping process, a raw glass sheet workpiece and mold are heated up to the working temperature (or soaking temperature) and then slumped by its own weight or (negative) vacuum pressure. Controlled cooling of the slumped glass mirror is carried out immediately after slumping is completed to keep the thermal shrinkage and residual stresses below the required levels after the molding process. As compared to conventional abrasive based process, thermal slumping is a high volume, low cost, and one-step fabrication process. More recently, glass thermal slumping process has even been used to fabricate the segment of X-ray telescope mirrors and other extremely high precision glass optics [13,14]. Based on these successful applications, glass thermal slumping process is becoming a promising new method for fabricating solar optical components at an affordable cost.

In this paper, a two-stage nonimaging freeform concentrator was designed. A ray-tracing simulation was performed to evaluate the system design. Thermal slumping process was proposed to fabricate glass mirror as the designed primary mirror for high concentration photovoltaic systems. An easy to machine MACOR® glass–ceramic was chosen as the mold material to reduce the total cost of fabrication process. Experiments and FEM simulation were performed to improve the slumping process and compensate for the mold design. Finally, the slumped glass mirrors were evaluated for surface quality and curvature accuracy using coordinate measurement machine (CMM) and atomic force microscope (AFM).

2. Freeform optical design

2.1. Optical design

In this section, the concentrating optical design is based on the freeform optics using a geometrical approach. To satisfy the requirement of uniform irradiance on the receiver's surface, a two-surface design method of freeform surface based on the Kohler integrator arrays was proposed. In the Kohler integrator system, the rays emitted by one point at the source must illuminate the entire target [15,16]. For a concentrated solar photovoltaic system, this means that the light rays impinging on the primary surface have to be redirected to the entire receiving photovoltaic cell surface at any given incidence angle within the acceptance angle. In addition, to achieve a uniform irradiance distribution, the rays arriving at any point on the target must come from every point of the light source.

The integrated concentration Kohler optical design consists of two imaging optical reflective surfaces (primary and secondary). The secondary is placed at the focal plane of the primary, so that the primary surface images the sun on the secondary surface and then the secondary images the primary on the target cell surface. Since the incident light from the sun can be treated as paralleled rays with different incident angles, the primary surface was selected as the parabolic segment to focus the incident light to the secondary surface. To ensure uniform light distribution, ellipsoid surface segments are used to image the primary surface on the target surface. Fig. 1 illustrates the two-stage mirror surface system. The design algorithm detail is described below.

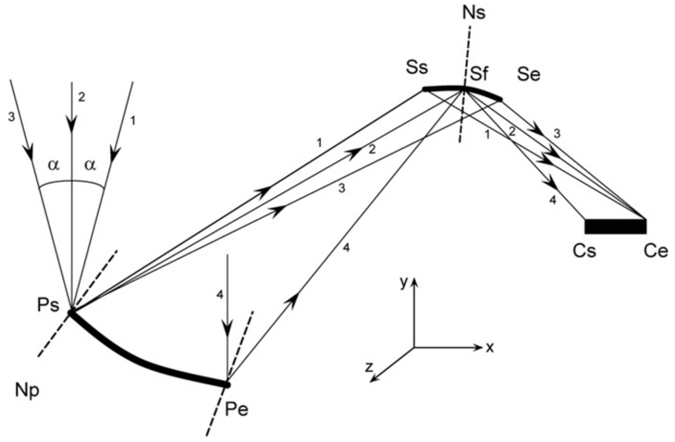

Fig. 1. Freeform secondary surface imaging of the primary surface on the photovoltaic surface (C_s–C_e).

a. The starting points of the primary mirror and secondary mirror are given as the initial calculation starting position as P_s (P_{sx}, P_{sy}, P_{sz}) and S_s (S_{sx}, S_{sy}, S_{sz}). At the same time, the position and size of the photovoltaic cell are also defined by a pair of pre-defined start and end points (C_s and C_e).
b. According to the rules of the edge ray principle, an ellipsoid surface (S_s–S_e) is initialized using points P_s and C_e as the focal points and passing point S_s. The size of this ellipsoid is controlled by the required acceptance angle at the primary surface, shown as ray 2, 3 in Fig. 1. After being reflected by the ellipsoid surface, all incident rays within the acceptance angle at point P_s are focused at target surface point C_e, according to the reflective property of the ellipsoid surface.
c. By defining that point S_s is passed through by the reflected line 1 from point P_s with maximum incident angle α, the normal direction N_p of primary surface at point P_s can be calculated by the vector form Snell's law as expressed in Eq. (1)

$$\boldsymbol{r}=\boldsymbol{i}-2(\boldsymbol{i}\cdot\boldsymbol{n})\boldsymbol{n} \tag{1}$$

In this equation, incident direction $\boldsymbol{i}$ and reflection direction $\boldsymbol{r}$ both are known from the geometrical assumption, and then the normal direction $\boldsymbol{n}$ can be derived.

d. After the normal direction N_p at point P_s is known, the direction of the reflected incident ray along the normal direction can be calculated using Eq. (1), shown as ray 2 in the figure. The point of intersection between the reflected ray and the pre-defined ellipsoid S_s–S_e is defined as the focal point S_f of the primary parabolic segment passing point P_s. The intersection point can be found using the bisection method [17]. Using the point P_s and the focal point S_f, the primary parabolic segment profile can be derived as P_s–P_e.
e. According to the incident light and reflected light path pair (line 2), the normal direction N_s at the point of intersection S_f can be calculated using Eq. (1). In addition, the reflection of the normal incident ray reaching the end point of the parabolic segment is reflected to point C_s by the ellipsoid surface at the point S_f. Therefore, by calculating the direction of the reflection of line C_s–S_f, the position of the end point P_e on the parabolic