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Analysis of optical properties and geometrical factors of linear deflection surface concentrators

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ABSTRACT

A deflection surface concentrating mirror technology is proposed in this paper. Unlike traditional shaping technologies such as those used to manufacture parabolic mirrors and cylindrical mirrors, this method features no direct contact between the glass surface and the mold during the hot-bending process, freeing the mirror from any subsequent damage. This report primarily discusses the variation in roughness *Ra* of the ultra clear float glass surface before and after the hot-bending and demonstrates that the loss of ultraviolet and the visible portions of the solar energy spectrum on the concentrating mirror due to scattering may be significantly reduced by adopting this shaping technique and consequently improving the optical performance of the mirrors. Based on the present study, the optical properties of the deflection surface and the influence of the glass size and tailoring schemes on the optical properties were determined. The results established that tailored deflection surfaces could be used as reflective concentrator surfaces, and Fresnel concentrating groups having a high concentration ratio may be constructed by combining multiple deflection surface mirrors. Further, a deflection mirror group prototype was introduced for verification, including its basic parameters and manufacturing cost which would drop remarkably if the mirrors were mass-produced. Thus, the present technique may not only achieve higher optical efficiency than the contact shaping technologies, but also reduce the manufacturing cost significantly, making it widely applicable in the field of high-temperature solar thermal utilization.

1. Introduction

Parabolic trough technology is presently the most common collector for linear concentration [1]. Being transparent, glass plays an important role in concentrating solar power (CSP) systems [2,3]. Currently, the main technique for manufacturing parabolic glass mirrors is the hot-bending method that replicates the profile of the pre-fabricated mold surface onto the slumped glass work-piece during which it is essential that the original glass sheet fully touches the mold under high temperatures to achieve a precise customized surface shape, consequently increasing its surface roughness *Ra* to about 40 nm [4,5]. According to Tang, Gu and Liu's study [6], such mirror surface specularly reflects at wavelengths $\lambda < 640$ nm of the solar spectrum with difficulty and the energy within this part of solar spectrum accounts for up to 40.2% of the total solar energy [7]. Therefore, the contact between the glass sheet with the mold during the hot-bending process inevitably contributes to the substantial loss of the mirrors' optical coefficient, irrespective of solid molds or frame molds with customized surface shapes. As shown in Fig.1(a) and (b), a solid mold uses a curved panel to constrain the glass deformation while a frame mold uses a curved frame to achieve the same effect.

About 99% of the total energy in the solar spectrum reaching the earth's surface is contained in the spectrum at $\lambda > 300$ nm [7]. A reflective surface is required to satisfy the conditions for its roughness $Ra \leq 18.75$ nm to specularly reflect in this part of the spectrum [6]. In fact, the *Ra* of a fresh sheet of ultra clear float glass is not greater than 10 nm. Developing a technique which ensures less variation in the hot-bending process, so that the *Ra* of glass would be less than 18 nm, would permit specular reflection of the total solar spectrum on the surface of mirrors fabricated by using the technique and consequently increasing the optical performance of the mirrors.

In the hot forming process, a reflective mirror manufacturing method is developed to protect the glass sheet from surface damage by avoiding contact between the glass and the mold used for shaping. The shape of the reflective mirror obtained by adopting this method is not parabolic, but a deflection surface. In fact, the deflection of the beam and board components has been extensively studied earlier, including thermal deformations of glass [8,9] which is usually considered as a disadvantage, and the methods to avoid or decrease it in theory. The manufacturing process of reflective mirrors is proposed to benefit from the

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Nomenclature

A_a	aperture area, m^2
A_r	receiver area, m^2
b	glass width, mm
C	geometric concentration ratio, $C=A_a/A_r$, dimensionless
C_{max}	maximum geometric concentration ratio for a deflection surface mirror when it is tailored by the ratio $Ta_{,max}$ of its span, dimensionless
E_1	Young's modulus of glass in Kelvin deformation process, GPa
E_2	Young's modulus of glass in Elastic deformation process, GPa
f	focal length, mm
h	glass thickness, mm
I	sectional moment of inertia of the sheet glass, $I=\frac{bh^3}{12}$, kg/m^2
l	glass length or hot-bending span of a deflection surface mirror, mm
l_r	the remaining span of a deflection surface mirror after tailored, mm
g	acceleration of gravity, m/s^2
q	uniform load due to glass weight, N/m
t	time, s
T	furnace temperature, K
T_o	ambient temperature, K
W	image width on the flat receiver located on line AA ′, mm
$W_{,Cmax}$	image width of the mirror tailored with the tailoring scheme for C_{max}, mm
x	the horizontal distance between the deflection calculation point and the left supporting point, mm
$y(x, t)$	the deflection at horizontal coordinate x at time t, mm
y_{max}	the maximum deflection of a deflection surface, mm
Δy	deflection difference, mm
η_1	viscosity coefficient, kg/(ms)
λ	the wavelength of the solar radiation, μm
τ_1	delay time, $\tau_1=\frac{\eta_1}{E_1}$, s
Ra	glass surface roughness, nm
Ta	tailoring ratio, dimensionless
$Ta_{,c}$	economical tailoring ratio, dimensionless
$Ta_{,max}$	tailoring ratio for C_{max}, dimensionless

Abbreviation

CECs	compound elliptical concentrators
CPCs	compound parabolic concentrators
CPV	concentrating photovoltaic
CSP	concentrating solar power

thermal deformations. In general, it is known that the concave mirror has concentrating characteristics. In this report, the surface of the glass after the deformation of deflection in the furnace, the characteristics of this concentrating mirror and its practical utilization will be discussed in detail.

During production, the control of surface accuracy of the reflective mirrors that determines its shape, size and image position on absorber is of great importance along with the ability to meet the requirements of the design. A parabolic mirror glass forming technique is used to duplicate/transfer the parabolic surfaces of the mold to the glass. As a result, the accuracy of the surface of the parabolic mirror is determined by the precision of the mold surface [10,11]. On the other hand, in the deflection surface shaping technique, many complex factors related to the accuracy of deflection surface mirrors, such as the geometry and chemical composition of the original glass plate, the constraints on the mold, the variations in temperature and other factors that vary with space and time are significant. This report focuses only on the basic geometric aspects and the concentrating characteristics of the deflection surface mirror. Since other factors would change the geometry of the deflection surface directly, their influence on the accuracy of deflection surface mirrors can mostly be substituted by the influence caused by geometric factors.

2. Introduction of deflection surface

2.1. Formation mechanism

Ultra clear float glass is used to manufacture deflection surface mirrors, due to its good optical performance and excellent durability for the collection of solar energy and is currently very popular in the concentrating photovoltaic (CPV) and concentrating solar power (CSP) systems [14–16]. Its optical and physical parameters [17] are listed in Table 1.

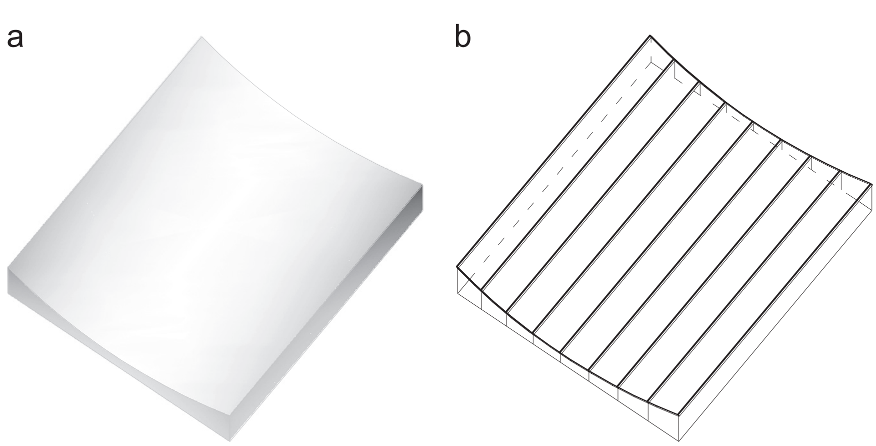

Fig. 1. The common shapes of molds used for mirror shaping: (a) solid mold and (b) frame mold.