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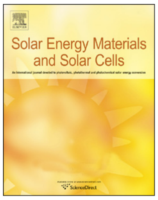

Analysis of residual stress for mismatch metal–glass seals in solar evacuated tubes

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ABSTRACT

The residual stress of mismatch seal between borosilicate glass 3.3 and stainless steel is analyzed for metal–glass solar evacuated tubes in this paper. As borosilicate glass has a much lower limit of stress than metal, a tube model with different sizes and shapes of metal and glass is simulated to determine the magnitude and profile of the residual stress in the glass region. The simulation results show that the maximum magnitude of the hazardous tensile stresses occurs at a few millimeters above the sealing area, not in the contact position; and the thickness of metal is the most important parameter of the seal which affects the stress level. The stress magnitude increases dramatically when the thickness of stainless steel increases from 10 to 60 μm. Therefore, to avoid breakage of the seal, the thickness of metal should be less than 40 μm. In addition, it is shown that both the cross-section shape of the metal ring and the contact length in the glass have a considerable impact on the stress. The stress level increases significantly with the increase of depth of the metal ring embedded in the glass. Comparison between a metal ring with trapezoidal cross-section and one with rectangular cross-section of equivalent mean thickness reveals that the former leads to smaller residual stress. Furthermore, the results show that variation in the glass tube dimensions, in compare to the metal ring parameters, has less effect on the residual stress level in the seal area. An increase in the thickness of the glass tube decreases the stress noticeably, whereas an increase in tube radius has a negligible impact. Finally, it is shown that the simulation results are in good accordance with results of experiments using samples of mismatch seal between borosilicate glass 3.3 and stainless steel successfully fabricated according to our proposed parameters.

1. Introduction

One of the most important components of any concentrated solar power system is solar evacuated tube, which is also known as Heat Collection Element. Solar evacuated tubes operate with high solar thermal conversion efficiency, generally more than 60%, which has a great influence on the concentrated solar power plants' overall performance [1,2]. Therefore, the process of design and manufacturing of these solar evacuated tubes is an important challenge in order to increase the solar conversion efficiency of solar plants. The typical design and specifications of these receivers are presented in [3,4], and their main issues and shortages are also discussed.

Even the best designed solar tubes have relatively high failure rates, about 30–40% within a period of 9–11 years of their operation [5]. These failures can take place due to different reasons, such as flux induced thermal stress, shocks and vibrations. These kinds of issues may cause different consequences like tube vacuum loss, fracturing of the glass and degradation of the solar selective coating. However the biggest issue is the glass breakage in the metal–glass sealing area of the tube due to thermal residual stress [5,6]. This problem has been the subject of several studies and research. For example, a theoretical analysis has been carried out about the residual stress in metal-to-glass seals to derive an analytic solution for a tubular sealing structure in [7]. On the other hand, the residual stress distribution is investigated in metal–glass seals by finite element modeling and simulation in [6] and the results are compared with measurement results obtained by applying the photo-elastic technique.

However in the aforementioned studies, the residual stress in the sealing area of the metal–glass contact is only studied for DM 308 glass and Kovar alloy. Although they have similar thermal expansion coefficients, DM308 glass and Kovar alloy do not possess appropriate outdoor durability for long-term operations [8].

In order to overcome this shortcoming, the use of borosilicate glass 3.3 and stainless steel is suggested in this study because

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these materials have excellent durable outdoor performance. However, there is a big difference between their thermal expansion coefficients which makes it difficult to seal. Ref. [9] has tried to find a solution for the stress equations of such mismatch seals, but the solution is too complex and only valid for the conventional rectangle shape of the metal-to-glass contact. In this paper we adopt the finite element method to simulate the residual stress of mismatch seal made of borosilicate glass 3.3 and stainless steel with different shapes and sizes.

2. Modeling and simulation

2.1. Solar tube geometry and materials

Fig. 1 shows the simplified structure of the solar evacuated tube used in our study. The metal–glass contact area is enlarged to illustrate the important dimensions in the lower part more precisely. The axes defined based on the cross-sectional view of our configuration are shown in the figure as *X–X* and *Y–Y*. All residual stress profiles resulting from the simulation will be drawn with respect to these axes.

The type and properties of the materials used in our studied solar tube are listed in Table 1 [10,11]. As mentioned earlier, a solar evacuated tube made of borosilicate 3.3 and stainless steel 304 will be considered in this study.

2.2. Metal-glass sealing stress, the causes and the breakage limit

During the manufacturing of a seal, residual stress is produced unavoidably. This occurs during the cooling stage from the transition point of glass ($T_0=525\ ^\circ\mathrm{C}$) to room temperature ($T_a=27\ ^\circ\mathrm{C}$) and is the main reason for the breakage of the seal. In order to have a reliable seal, it is essential to keep the magnitude of tensile residual stress significantly lower than the maximum permitted stress as defined by the limit provided by the solar tube manufacturers. This criterion can be expressed as shown in Eq. (1). The breakage limit for borosilicate glass 3.3 is defined as 13 MPa by the manufacturers; therefore the maximum level of the simulation results should be considerably less than this limit.

$$W_{\mathrm{m}}=0.5((W_{\mathrm{a}}+W_{\mathrm{b}})+(W_{\mathrm{c}}+W_{\mathrm{d}})) \tag{1}$$

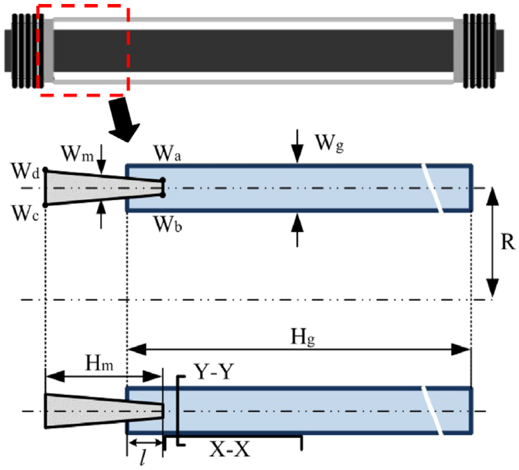

Fig. 1. Simplified configuration of metal–glass contact seal in the structure of solar evacuated tube (drawing is not in scale).

Table 1
Typical values for the material properties.

Properties	Material	
	Borosilicate 3.3	Stainless steel 304
Thermal expansion [1/K]	3.3×10^{-6}	17.5×10^{-6}
Young's moduli	64	193
Poisson ratio	0.2	0.3

2.3. Modeling

According to the configuration and material properties described above, a comprehensive model of the solar receiver tube with parametric dimensions is developed to carry out the required evaluations for this research. The model is developed and implemented in a finite-element software package called COMSOL Multiphysics. Since the studied configuration is an axisymmetric two-dimensional geometry, the “2D-axisymmetric” option of COMSOL is used to reduce the level of complexity of three-dimensional object modeling, as well as the required simulation time and computing resources. The “Solid Mechanic” option of the “Structural Mechanical” physics is chosen as the appropriate module to calculate the residual stress tensors. Furthermore, a parametric sweep nonlinear solver is used as the simulation method, while an ultra-fine meshing option is applied to study the narrow width areas more precisely. All the simulations are carried out by COMSOL Multi-physics Version 4.2, running under Microsoft Windows 7 operating system. The outcome of these simulations will be presented and discussed in the following section.

3. Results and discussions

3.1. Simulation results

In the first step of our simulations, a metal–glass seal with the simplest shape of metal ring cross-section will be studied. According to the configuration illustrated in Fig. 1, the general form of the metal ring cross-section can be shown by a trapezoidal shape. Using this form makes it possible to introduce different shapes by defining the positions of the four corners of the shape in the simulation software. For the case of rectangular form, it is enough to use an average thickness to represent the dimensions of the metal ring component, as defined by Eq. (2).

$$\sigma_{\max}<\sigma_{\mathrm{limit}}=1.3\times10^{7}\ \mathrm{Pa} \tag{2}$$

Fig. 2 shows a 2D illustration of the residual stress level for this configuration of the solar tube. The highest level of tensile stress occurs in the section of the metal ring that is embedded in the glass. However, due to the metal properties and its ability to endure high stress levels, this will not lead to glass tube breakage or other problems the seal.

In contrast to the metal region, the glass region is extremely sensitive to residual stress. In this region, the maximum level of tensile stress takes place at the contact position of the glass tube and metal ring. Ignoring this very narrow area (at the metal tip), it can be said that the breakage of the seal usually happens in the glass tube region, a few millimeters above the metal–glass contact region.

As defined in Fig. 1, in order to draw the calculated stress profiles more visibly and precisely, it is preferable to illustrate them using line graphs according to *X–X* and *Y–Y* sections. Drawing the graph according to the *X–X* axis shows the distribution of the *z* component of the residual stress along the outer surface of the glass tube. Drawing the graph according to the *Y–Y* axis shows the distribution of the *z* component of the residual stress along the radial direction, inside the glass tube wall. Fig. 3