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Soda Lime Silicate Glass Tube–Titanium Inset Joining by O_2/Propane Flame Work in Air

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Glass–metal joining is important for improving efficiencies of heat collecting units employed in linear parabolic sun collector systems. Soda lime silicate glass tube–titanium inset joining was made by using propane/O_2 flame working in air. Optic and scanning electron microscope investigations of joined samples showed oxidation of titanium in air and its reaction with glass leading bubble formation. ANSYS14 Multiphysics modeling of residual joining stress levels suggested that titanium inset and soda lime silicate glass had rather low residual stress levels due to close thermal expansion coefficients. For the used sample dimensions with uniform glass tube shape, highest residual maximum principal stress was $\approx$ 60 MPa and minimum principal stress was $\approx$–40 MPa for the glass at joining interface. However, glass shape was found to be affecting residual stresses during bonding and shape defects like groove formation increased residual minimum principal stress levels to –90 MPa near joining interface. Some microcracking of glass was also observed in groove region. Bubble formation in glass near reaction interface was also found to be involving crack formation and its propagation as well. Therefore, controlling glass shape and interfacial reaction was found to be important for successful titanium inset–soda lime silicate glass tube joining by flame working in air.

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PACS/topics: soda lime silicate glass tube, titanium inset, O_2/propane flame work, interfacial reactions, residual joining stress modelling, ANSYS 14

1. Introduction

Glass to metal joining is important and required for improving efficiencies of heat collecting units employed in parabolic solar collectors [1, 2]. Borosilicate glass–kovar (Ni-Co-Fe) alloy joining is often preferred due to their closely matched thermal expansion coefficients [2–4]. However, kovar alloy is expensive. If soda lime silicate glass tube to titanium joining is achieved, it would be more economical alternative. Since, soda lime silicate glass is an economical glass and titanium is more economical compared to kovar alloy [5, 6]. Joining of soda lime silicate glass to titanium would be possible due to having close thermal expansion coefficients: 10.1×10^{-6} °C^{-1} for titanium and 9.1×10^{-6} °C^{-1} for soda lime silicate glass [7, 8]. Although there are some studies of soda lime silicate based glass — ceramic coatings for titanium for oxidation protection, there is not any study for O_2/propane flame work joining of commercially available soda lime silicate glass to titanium in air [9–11]. In this study, joining of soda lime silicate glass tube to titanium inset by employing O_2/propane flame work air is provided. Interfacial reactions between soda lime silicate glass and titanium during flame work joining is investigated. Maximum and minimum principal residual stresses levels are modelled based on finite element method by employing ANSYS 14 Multiphysics simulation software. Finally, important points for successful joining of soda lime silicate glass tube to titanium inset by flame work in air are given.

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2. Experimental procedure

For O_2/propane flame work joining, soda lime silicate glass tube (Schott Ar glass) and commercially pure titanium (Alfa Aesar, 99.5 wt%) were used for joining. Soda lime silicate glass tube was annealed at 550 °C for 30 min to remove any preexisting residual stresses prior to joining. Then, the glass tube was taken out of annealing oven, titanium inset was placed into the glass tube, O_2/propane flame was applied glass from outer side by using a hand torch till the glass tube was locally softened, reacted and bonded to the placed titanium inset in total of 3 min. The bonded glass tube–titanium inset was then placed back into the oven rapidly, annealed at 550 °C for 30 min and cooled back in 3 h to the room temperature.

The joined soda lime silicate glass tube–titanium inset was cut by diamond saw and taken partially to polymer mold to investigate titanium–glass joining interface. Optic microscope investigations were done in dark field imaging mode by using Zeiss Axiotech model light microscope. Scanning electron microscope (SEM) investigations were done by employing JEOL 6060 model scanning electron microscope with secondary electron imaging mode. Residual maximum and minimum principal stresses were modelled by employing ANSYS 14 Multiphysics Finite Element Method Software. Used sample size and dimensions with modelling were: soda lime silicate glass tube (100 mm long) having 13.5 mm outer diameter with an 1 mm wall thickness, the titanium inset having top region (2.5 mm long) with 12.5 mm outer diameter and 1.75 mm wall thickness and bottom region (5.0 mm long and bonded to glass tube interior) with 11.5 mm outer diameter and 1.25 mm wall thickness. Table I provides material properties employed in residual stress modeling. Calculations were done considering residual stresses were developed due to cooling down of bonded glass tube–titanium inset joint from thermal stress relieving annealing temperature at 550 °C to room temperature. While the soda lime silicate glass was considered as brittle elastic material not showing any plastic deformation, the titanium was considered as both elastic and plastic material showing work hardening with plastic deformation if stress levels were high enough.

TABLE I

Materials properties used for residual joining stress calculations

Materials property	Soda lime silicate glass	Ti
thermal expansion coefficient α [°C^{-1}]	9.1×10^{-6} [7]	10.1×10^{-6} [8]
Young modulus E [Pa]	73×10^{9} [7]	116×10^{9} [8]
Poisson ratio υ	0.22 [7]	0.34 [8]
yield strength σ_y [Pa]		240×10^{6} [12]
true stress σ_{true} level [Pa] at true strain ε_{true} level of 0.2		550×10^{6} [12]

Fig. 1. O_2/propane flame work joined soda lime silicate glass tube–titanium inset sample: (a) whole sample, (b) crack free region in closer view having uniform bonded glass shape, and (c) crack formed region where groove defect of bonded glass promoted cracking.

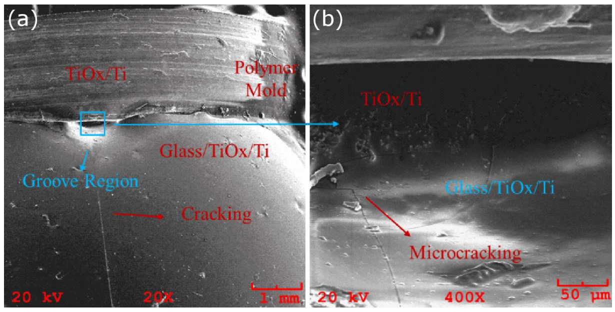

Fig. 2. Scanning electron microscope secondary electron mode images of O_2/propane flame work joined sample: (a) low 20× magnification image of groove region where cracking was observed, (b) higher 400× magnification image of inside groove region where glass micro cracking initiated at glass–Ti-inset reaction interface.

3. Results and discussion

Figure 1a shows that the glass tube could be joined to titanium inset with some success. As seen from Fig. 1b where bonded glass shape was stayed uniform, soda lime silicate glass tube could be joined to titanium inset without any macrocrack formation at glass by employing O_2/propane flame working in air. However, a macrocrack formation starting from bonded glass–titanium inset region was observed for the glass region having shape defect of groove formation in glass tube region as illustrated in Fig. 1c. This suggested that shape of the bonded glass was important and affecting residual stresses developed in joined glass region and could promote crack formation.

Figure 2a and b illustrates top view scanning electron microscope secondary electron images of O_2/propane flame work joined soda lime silicate glass tube–Ti inset sample. Figure 2a showed that crack formation was started inside the groove region and propagated through the joined tube. This suggested that residual stresses were higher in the groove region. Crack formation was found to be originating at glass–Ti inset joining interface inside the groove region in Fig. 2b higher magnification view of inside of groove region. This suggested that reaction interface between glass and Ti inset was affecting and important for microcrack initiation.

Figure 3a and b is optic microscope image illustrating soda lime silicate glass tube–Ti inset joining interface at groove defect region where microcracking was observed. Figure 3a showed that microcracking of glass was forming in groove defect region near joining interface. As seen in Fig. 3b (higher magnification 20× image) that bubbles formed at interface due to Ti/TiO_x–glass reaction caused microcracking. This suggested that formation of gas bubbles at joining interface was affecting microcrack initiation and its propagation.

Figure 4 presents modeled residual maximum and minimum principal stress levels of joining samples by employing ANSYS 14 Multiphysics Software. According to Fig. 4a, joined glass tube had rather low residual maximum principal stress levels with the highest levels at the order of 60 MPa observed for close to joining interface toward glass top layer and inside groove region. Figure 4b showed that residual minimum principle stress

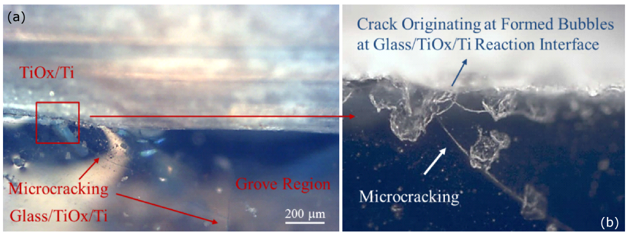

Fig. 3. Optic microscope images of O_2/propane flame work joined soda lime silicate glass tube–titanium inset joining interface taken at dark field imaging mode: (a) low 5× magnification image showing cracking of grove region at glass, (b) higher 20× magnification image of groove region showing cracks originating and propagating at joined glass/TiO_x/Ti interface where bubble formations were observed.

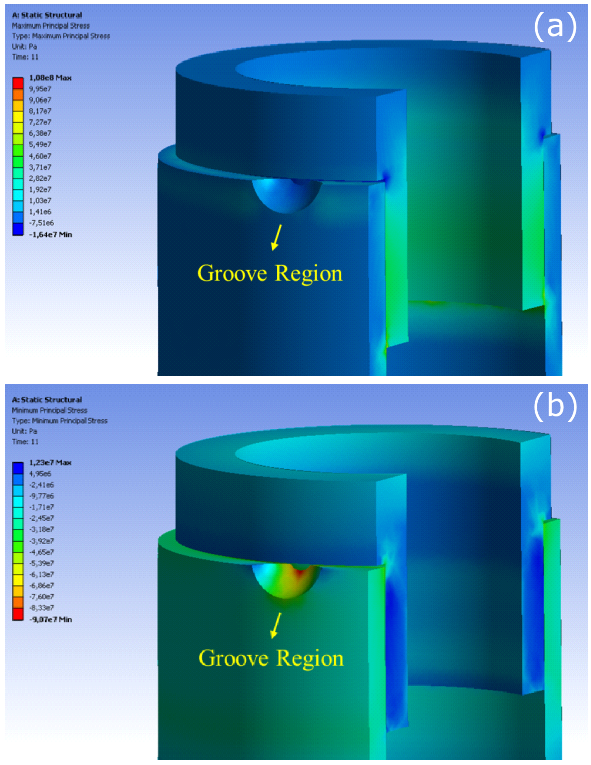

Fig. 4. Residual joining stress levels of O_2/propane flame work joined soda lime silicate glass tube–titanium inset for used sample profile and simulated by employing ANSYS 14 Multiphysics Simulation Software: (a) maximum residual principal stress levels for groove region and cross-section region glass having uniform shape, (b) minimum residual principal stress levels for groove region and cross-section region glass having uniform shape.

levels were slightly lower with the lowest at the order of –40 MPa observed at glass titanium joining edge near interface. However, residual minimum principal stress levels were increased and reached to –90 MPa levels at joining interface in groove region. This showed that the groove region was in fact leading higher residual stresses and agreed well with experimental observation of cracking only in groove region but not in joined glass having uniform shape.

If sample dimensions were carefully selected to minimize residual stresses and bonded glass shape was controlled well not to lead stress concentrations, it is possible to join soda lime silicate glass tube–Ti inset by employing O_2/propane flame work in air successfully. Modelling results showing rather low residual stress levels agreed well with experimental findings of not observing any microcracking for uniform glass shape. Having similar and slightly lower thermal expansion coefficient for glass (9.1×10^{-6} °C^{-1}) compared to titanium (10.1×10^{-6} °C^{-1}) produced rather low residual stress values. However, when there was a glass groove formation shape defect, residual stress levels increased microcracking in this region. There were also some bubble formations at joining glass–TiO_x/Ti reaction interface. In literature, bubble formation was reported to be due O_2 release at reaction interface involving dissolution of titanium oxide into glass and following with reaction of silicate based glass with titanium surface [11, 13]. Formed bubbles at interface also caused microcrack formation in groove region where stress concentration was observed. Therefore, bubble formation at joining interface was needed to be minimized and controlling glass shape to prevent stress concentration was essential for successful flame work joining.

4. Conclusion

Soda lime silicate glass tube–Ti inset joining was achieved in air with O_2/propane flame work in air. For uniform joined glass shape no microcracking was observed suggesting residual stress levels stayed low. ANSYS14 simulation results suggested and agreed well with experimental findings that for the studied sample dimensions, glass tube experienced rather low residual principal stress levels with highest principal maximum stress levels of 60 MPa and minimum principal stress levels of –40 MPa near joining interface at glass tube–titanium inset. Shape of glass was found important and groove formation in glass tube caused increased minimum principal residual stresses to –90 MPa levels. Bubble formation at glass –TiO_x/Ti bonding interface during reaction was observed and found to leading to microcrack initiation and affecting its propagation in groove region. For successful soda lime silicate glass tube to titanium inset flame work joining in air, interfacial reactions leading to bubble formation needed to be minimized and residual stress levels needed to be kept low by controlling bonding glass shape carefully without leading groove defect formations.

Acknowledgments

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