Glass–Metal Joints for Solar Thermal Application: Associated Fabrication Problems and Structural Integrity Issues

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Abstract—*The Glass-Metal Joints (GMJ's) play a critical and indispensible role in parabolic trough collector system for solar power applications. The failure of glass-metal joint can lead to non utilization of the parabolic trough collector system causing not only monetary losses due to non- functioning of the solar thermal power systems but also posing a challenge towards the utilization of parabolic trough collector technology as an option for providing sustainable energy. The present paper highlights and reviews the current fabrication issues affecting the glass-metal joints and also entails the current issues in the structural integrity of these joints during operation and fabrication.*

Keywords: *Glass Metal Joints, Fabrication Processes, Structural Integrity, Parabolic Trough Collector*

INTRODUCTION

Glass-metal joints are in wide use since 19^{th} century, when electric bulb was invented. Nowadays, it is commonly used in the electronic industry, medical equipments like heart pacemakers& weaponry. It is also used in nuclear and thermal power plants. In nuclear plants, glass-metal joints have to resist high temperature, high neutron fluences and must be leak tight. These characteristics are difficult to obtain for a joint between dissimilar materials with very different material properties. To overcome these challenges, research input in this field is increasingly required.

CLASSIFICATION OF GLASS-METAL JOINTS

There are many ways to classify glass-metal joints for example according to the geometry of the metal part and the type of glass, variation in coefficient of thermal expansion. Classifications of glass metal joints are as follows:

Matched glass-metal joint: These type of glass-metal joint have the same thermal expansion coefficient for glass and metal components. **Unmatched glass-metal joint** has the different coefficient of thermal expansion for both glass and metal components. Matched joints are subdivided depending on the expansion of the glass. Hard Glasses have coefficient of thermal expansions lower than 6×10^{-6}/°C while soft Glasses have coefficient of thermal expansions higher than 6×10^{-6}/°C. Some of the hard glasses are borosilicate glasses while some of the soft glasses are soda glasses. The Unmatched glass-metal joints can be subdivided into **compression** and **ductile joints**. Housekeeper joint is the best example of ductile joint. A common example of a Housekeeper joint is a joint between glass and copper. Copper due to its high ductility is used in housekeeper joint though there is a mismatch in the CTE of copper and glass. The compression joints can be further divided in matched and reinforced compression joints. In the compression joint the compressive force is generated by the metal envelope on the inner glass containment, the metal used in comparison to the selected glass has a considerably higher coefficient of thermal expansion. Reinforced compression joints have a design where a metal pin with low coefficient of thermal expansion is surrounded by a glass having a higher coefficient of thermal expansion and which is further enveloped by a metal containment with even higher coefficient of thermal expansion. The reinforced compression joints are further subdivided into hard and soft depending on the type of the glass being used for fabrication of glass-metal joint. In the case of a matched joint, the joining is a result of a good chemical bonding at the glass/metal interface between the glass and metal oxide [10]. Matched joints can be made between metals, ceramics and other glasses with nearly same coefficient of thermal expansion. In these cases chemical bonding provides strength to the joint. In compression joints, the joint strength is due to the formation of a mechanical bond due to a compressive hoop stress between outer metal and inner glass portion of the glass-metal joint[1].

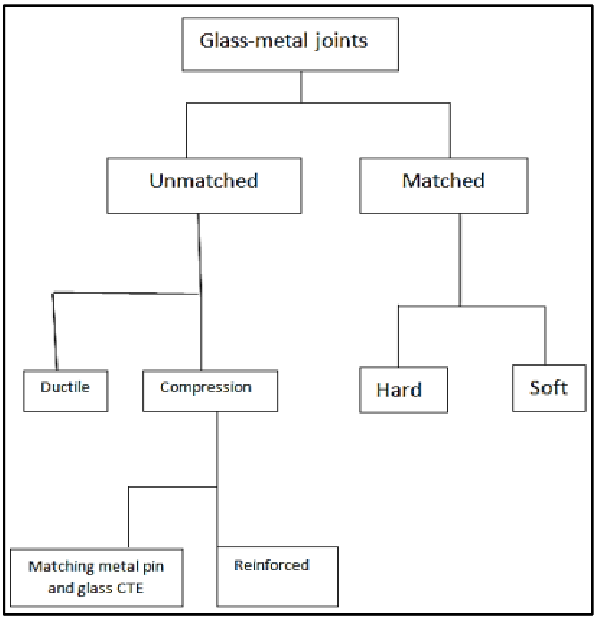

Fig. 1: Classifications of Glass-Metal Joints

FABRICATION PROCESSES

The fact that glass under suitable conditions, will bond well to a wide variety of metals and alloys has long been recognized and this has led to the development of many useful products[2].There are many fabrication processes for fabrication of glass-metal joint. Normally glass metal joining processes are classified as: liquid phase and solid phase joining processes. The various processes have been illustrated in Fig. 2.

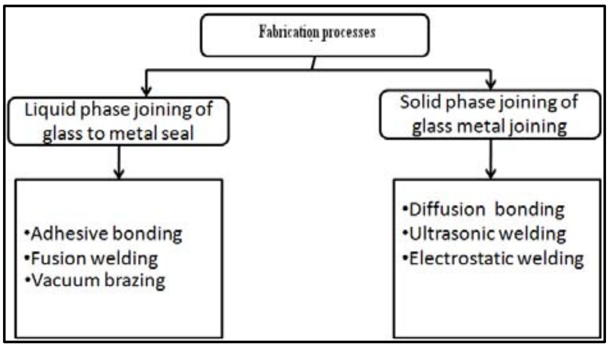

Fig. 2: Classification of Various Fabrication Processes for Glass-Metal Joint

For liquid phase joining, methods like adhesive bonding, vacuum brazing, and fusion welding are used as shown in Fig. 3.

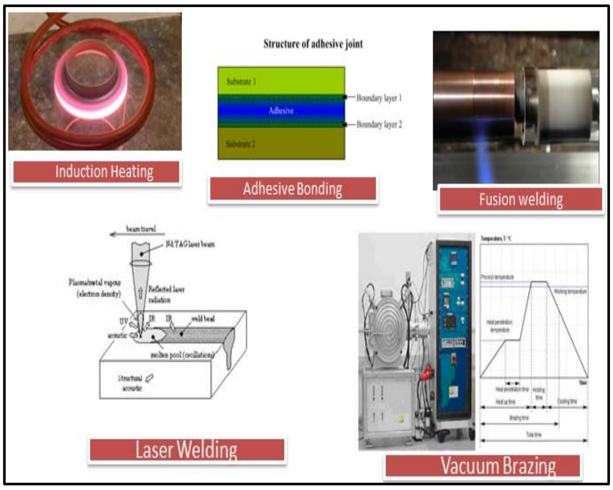

Fig. 3: Various Processes Used for Liquid Phase Joining [1]

Adhesive bonding provides uniform stress distribution, clean-looking joints, and is used for lighter structures and dissimilar materials with different thicknesses can be assembled. Its disadvantages include generally low durability; change in mechanical stress with time and requirement of surface pre-treatment.

In fusion welding, various sources of heat such as gas flame, laser, induction coil, etc. are used. Fusion welding creates differential temperature in the joints, which is problematic. Brazed joints between ceramics and metals have typically a mechanical strength of around 100 MPa [1]. The shear strength of the brazed joint depends on the brazing temperature and the brazing time [7]. Large shear stress induced at the interface suppresses the crack propagation along the interface. Brazing advantages are: it is useful in joining of dissimilar metals, the process can be automated and is suitable for large area joints. It has also disadvantages like surface needs preparation for wetting, formation of inter metallic compounds, thermal stresses, erosion of base material[1].

For solid phase joining, processes like diffusion welding, ultrasonic torsion welding and electrostatic bonding are used. Fig. 4 shows various solid state joining processes used for making glass-metal joints.

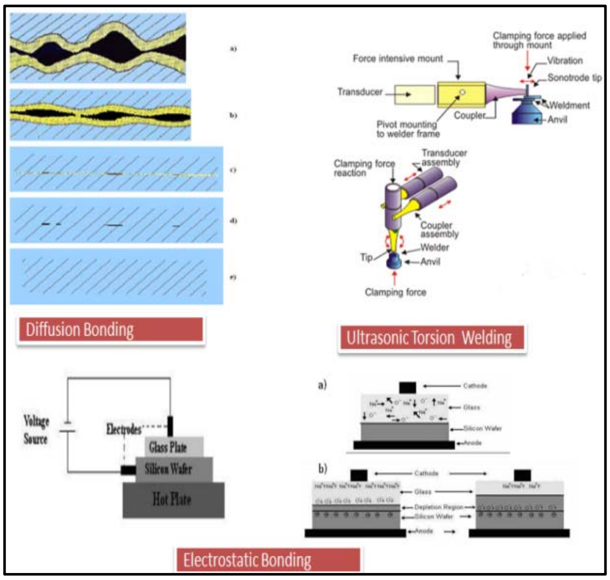

Fig. 4: Various Processes Used for Solid Phase Joining [1]

In case of ultrasonic torsion welding, it has got advantages like very short welding times (< 1 s), low welding temperatures, high automation potential& environmental compatibility and it can be applied under normal or specific atmospheric conditions. In diffusion welding, the advantages are like unchanged properties of parent material, possibility to bond similar or dissimilar metals and non-metals, high quality joints, automation of process is possible. There are no harmful emissions during the process. The diffusion welding process has got its disadvantages like excessive oxidation of joint, joining of stable oxide layer material is difficult, initial investment is very high, mass production is difficult. In Electrostatic bonding process, benefits are like direct joining process, clean process, possible to produce hermetic joints, relatively low bonding temperatures, no externally applied bonding pressure, rapid production process, simple equipment[1].

FABRICATION ISSUES

There are two major fabrication issues for joining of glass and metal i.e. the surface roughness and the surface contamination [5,6]. From the past study it is evident that, any surface exposed to the atmosphere will tend to react with available oxygen and water vapour in air [1].

Methods of removing or displacing the contamination and protecting against further contamination are material flow (like local deformation), fluxes, processes such as diffusion which induces displacement.

The adhesive bonding process though does not remove the contamination completely, it buries the contamination under the adhesive. During joint fabrication the surface roughness and non-planarity of a contact surfaces reduces the actual contact area between different materials significantly at the interface.

The solid phase diffusion based fabrication processes induce deformation and decrease surface roughness resulting in increased actual contact area. The liquid phase joining processes utilise the wetting characteristics of the liquid in forming a film at the interface and increasing the actual contact area between the joining parts.

For fabrication of glass metal joints by fusion processes, generally certain requirements are essential i.e. a) The glass should wet and adhere to the metal b) The linear expansion of the glass must match closely that of the metal over a wide range of temperature. c) The metal should have no thermal critical points (allotropic transformations) within the range of the highest temperatures reached in jointing and the lowest temperature reached in service. d) The glass should not re-boil when heated for making the joint, nor should the metal give off gases [9].

During fabrication studies by King *et al*. [14] and Donald [15] the requirements for a good adherence between the glass and metal have been elaborated.

It was observed that a good adherence is due to metal-metal oxide bonding. The metal-metal oxide bond formation occurs when the following conditions are met: A) there is saturation of an oxide of the metal in the glass at the interface B) the glass contains stable oxide in the glass solution which remains unaffected to reduction by metal.

The wettability of glass deteriorates in absence of oxygen during fabrication. For achieving high wettability the interface needs to be saturated with metal oxide.

STRUCTURAL INTEGRITY ISSUES

Even after lot of precautions in joining glass and metal, there are instances of observed degradation like Crack formation due to tensile residual stresses during fabrication, Vacuum leakage in glass-metal joints with usage, interfacial reactions causing formation of bulk phases reducing mechanical strength of glass-metal joints, generation of residual stresses due to mismatch in coefficient of thermal expansion and further degradation during Thermal cycling of glass-metal joints during operation andobservance of corrosion damage in glass-metal joints under service usage.

Another factor which creates problem in glass-metal joint is the presence of water in the glass. This creates thermodynamically favorable reactions between the water and diffusing metallic species and yields hydrogen gases [3].

The main problems for joining dissimilar materials are the differences in physical properties and undesirable metallurgical interactions such as brittle inter-metallic formation [4, 5].

Residual Stress

If there is a mismatch between the coefficients of thermal expansion between glass and metal being joined, the thermal residual stresses will develop in the joint when the joint is cooled to room temperature [1]. In Fig. 5 the residual stresses for a joint between a ceramic and a metal are displayed. Here the metal has a higher coefficient of thermal expansion than the ceramic. This would also mostly be the case for joining glass to metal. So as the materials are heated to be joined, the metal will expand more than the ceramic. After the joint is formed, the temperature must be cooled down back to room temperature. By this cooling the metal wants to contract more than the glass, but it is not possible anymore because of the joint with the glass. So this will lead to residual stresses at the joint [1]. In order to reduce residual stresses use of bulk property enhancement and stress relieving processes is required.

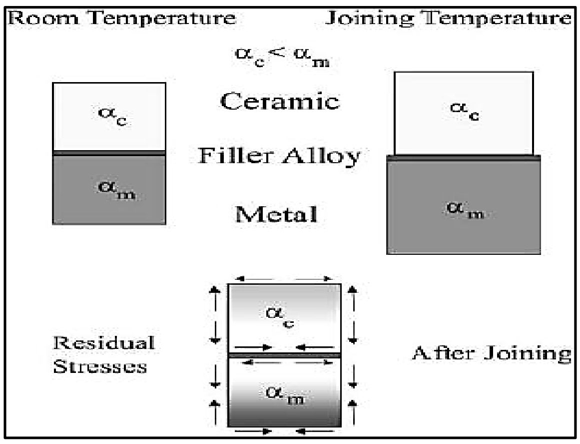

Fig. 5: Development of Residual Stresses in Metal-Ceramic Joint Due to Different Coefficient of Thermal Expansion [1]

Vacuum Leakage

Hermeticaly sealed glass-metal joints are increasingly being used in various applications that require vaccum tightness. In spite of the advances in technology it is practically impossible to manufacture a joint based enclosure or system that can be guaranteed to be leak proof. Fig. 6 illustrates the leakage rate measurement of a hermetically sealed system. The vessel with known volume (V_o) to be tested is connected by a valve to a vaccum pump. The change in pressure Δp is measured with time interval Δt. Different types of system possibilities exist: system is tight and clean (a), tight and not clean (b), not tight and clean, i.e.: ideal leak (c), not tight and not clean, i.e.: combination of leak and degassing (d).As can be seen in each case (except for a tight vessel) the pressure increase and the shape of the curve can be used to conclude on the type of leak. The leakage rate can be determined by using the following formula:

$$Q = \Delta p * V_o/\Delta t \text{ (mbarl/s)}$$

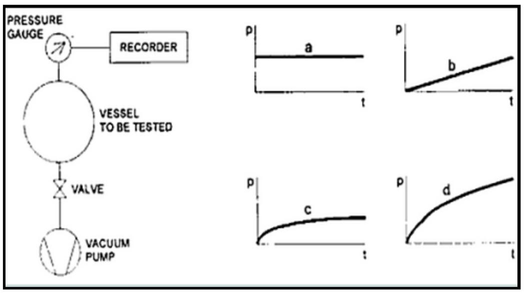

Fig. 6: Testing of Tightness by Increasing Pressure Method and Various Possible Results[13]

Figure 7 shows the maximum permissible leakage rates for different types of systems. The different techniques for measuring leakage rates and measuring range of these instruments for measuring leakage rates is shown in Fig. 8.

Element or System	Max. Permissible Leakage rate	Remarks
Chemical process Equipment	10^{-1} to 1 mbar l/s	Great process flow
Beverage can bottom	10^{-5} to 10^{-6} mbar l/s	Retention of CO2
Dynamic Pumped vacuums	10^{-5} to 10^{-7} mbar l/s	Permanent pumping
IC package	10^{-7} to 10^{-8} mbar l/s	
Pacemaker	10^{-9} mbar l/s	Long time implanted in body
Closed vacuum element	10^{-8} to 10^{-10} mbar l/s	Eg.TV and X rays tube

Fig. 7: Maximum Permissible Leakage Rate for Different System [13]

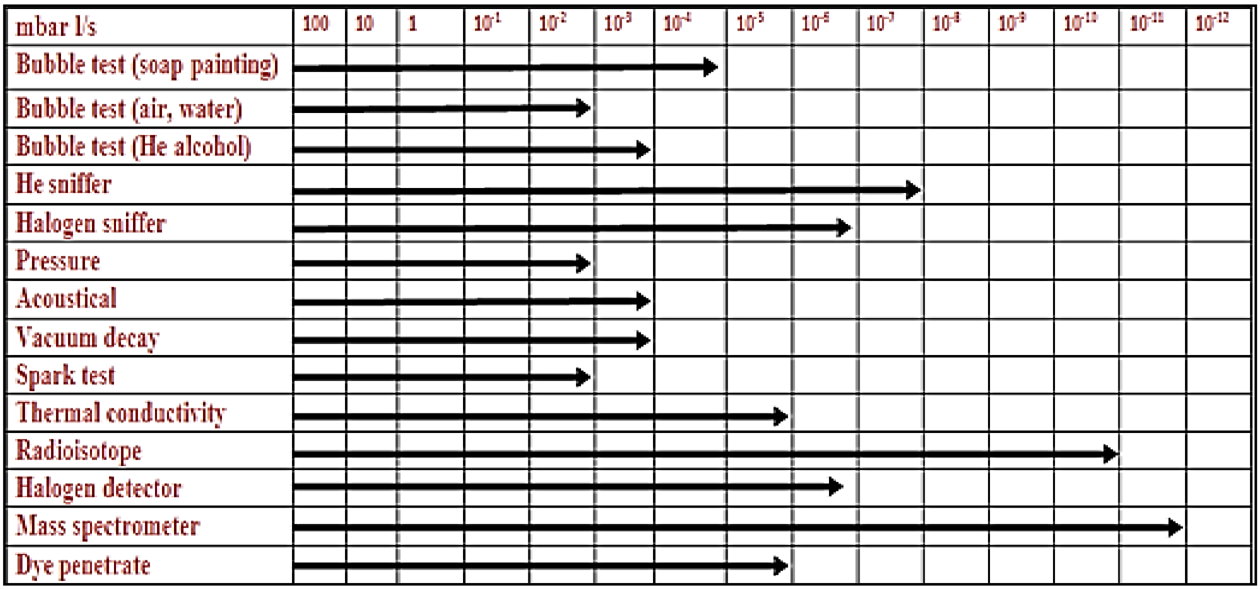

Fig. 8: Measuring Range of Various Instruments for Measuring Leakage Rates [13]

Crack Formation

Due to mismatch of coefficient of thermal expansion of glass and metal, formation of crack take place during fabrication of glass-metal joint as shown in Fig. 9. This presents a serious problem affecting the structural integrity of glass-metal joint. The thermal cycling during operation also results in cracking in the glass-metal joints.

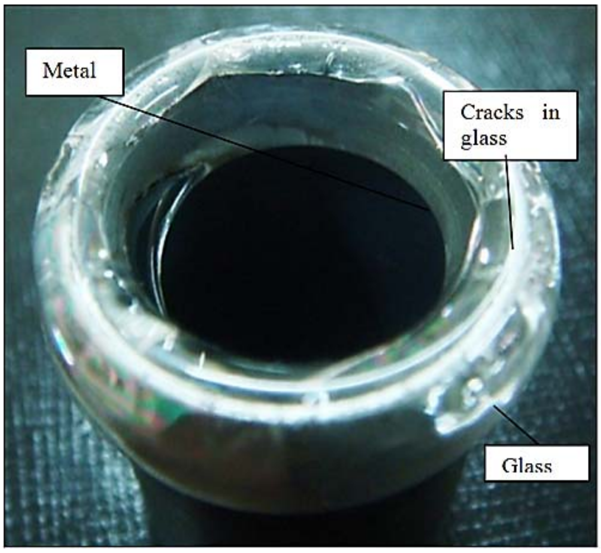

Fig. 9: Formation of Crack in Glass-Metal Joint due to Mismatch of Thermal Coefficient

Corrosion

Metals can be subjected to two kinds of corrosion: chemical or electrochemical (galvanic). In glass there are lots of blisters, which accelerate corrosion. Also there is fogging in the glass. Glass corrosion is primarily the result of hydrolysis, leaching, weathering and progressive crystallization—which is a natural occurrence through the passage of time. In Fig. 10, Scanning Electron Microscope image of corrosion observed in glass metal joint is shown.

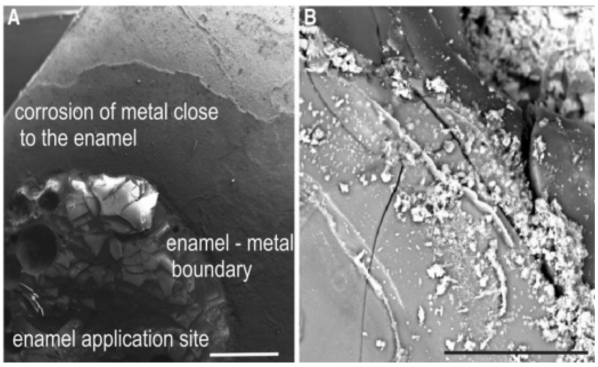

Fig. 10: Corrosion of Glass Metal Joint [8]

GLASS-METAL JOINT FOR PARABOLIC TROUGH COLLECTOR SYSTEM

The world is increasingly looking and moving towards utilising the renewable sources of energy and solar thermal is one of the suitable ways to provide the renewable energy in a sustainable manner. Parabolic trough plays a significant role in solar thermal power generation. Evacuated solar receiver tube is used in the parabolic trough collectors which decreases the convection losses and increase the life of solar selective coating on metal tube resulting in higher efficiency and longer life of the evacuated solar receiver tubes.

Glass-metal joints are employed in evacuated solar receiver tubes collector systems. The tubes are used to convert the solar energy into thermal energy and comprise a metal pipe with solar absorber coating on the surface and is surrounded by a evacuated glass envelope connected to metal bellows at the ends as shown by the schematic diagram in Fig. 11.

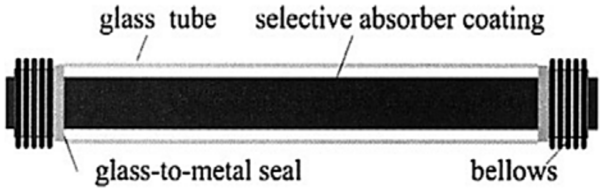

Fig. 11: Schematic Diagram of Evacuated Solar Receiver Tube [11]

The occurrence of fracture in the glass-metal joints during service is the main cause of failure in the parabolic trough collector systems [11, 12] as shown in Fig. 12. Further experimental research efforts and analytical studies are required for providing better understanding and enhancing the structural integrity of the Glass–metal joint under different operating conditions worldwide. The effect of thermal cycling during service, on residual stress generation, corrosion damage in the glass and metal and degradation in mechanical strength of the joint over the service period are a subject of research interest in the glass-metal joints being used for evacuated solar receiver tube.

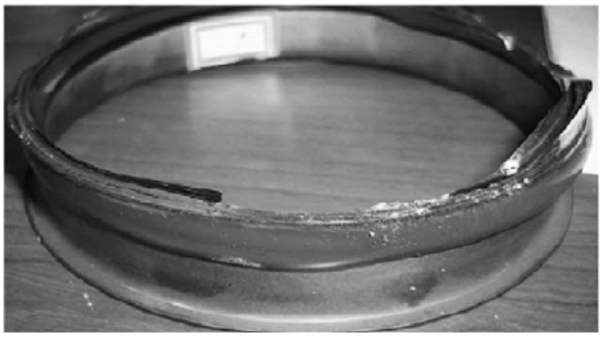

Fig. 12: Location of the Fracture [11]

CONCLUSION

Glass metal joints are extensively used in industries because of their numerous applications. The growth in development of solar thermal power systems based on parabolic trough collector has been stalled by the instances of damage of glass-metal joints. In the present paper, different fabrication methods and issues involved during fabrication of glass-metal joints are elaborated. For glass metal joining, automation of joining processes, surface roughness of interface involved, differential temperature during joining are some of the important challenges in fabrication. Structural integrity issues related to glass metal joints like corrosion damage, cracking during fabrication, vacuum leakage and interfacial reactions are some of the impediments in enhancing the overall structural integrity of glass-metal joints. The effect of thermal cycling during service, on residual stress generation, corrosion damage in the glass and metal and degradation in mechanical strength of the joint over the service period are a subject of current research interest in the glass-metal joints being used for evacuated solar receiver tubes.

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