Crack Analysis in Molybdenum Glass Melting Electrode

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Abstract: *Molybdenum's high melting point, high electrical conductivity, resistance to sagging at glass bath temperatures, and resistance to attack by most glasses make it an ideal material for glass melting electrodes. However, dissolution of molybdenum electrodes still occurs during glass melting and processing. A single piece molybdenum electrode was found to have cracked at the end of its service life. Post-mortem analyses also showed melting of the molybdenum material in the crack region. Finite element simulations using Abaqus were used to evaluate the crack formation. This study involved coupled thermal-mechanical modeling to predict the crack size and location. The FEA model was qualitatively successful in predicting the crack morphology based on very limited operational knowledge. The simulation results were compared with experimental results to evaluate necessary design changes for improving electrode life.*

Keywords: *Molybdenum, Glass melting electrode, Simulation, Abaqus, Crack, Thermal stress*

1. Introduction

Due to the conductive nature of molten glass, variety of different materials such as nickel alloys, tin oxides, carbon and platinum are used as electrodes to melt glass. Amongst all materials, molybdenum (Mo) is the most preferred due to its high strength and resistant to sagging at operating temperatures up to 1600 °C, chemical compatibility with wide array of glass compositions and resistance to erosion. A molybdenum glass melting electrode (GME) was returned for evaluation after failing in service. Very limited information about its operating conditions was provided by the user. The failed GME, shown in Figure 1, is referred to as "single piece" electrode since the entire body is produced by extrusion and machining of a large molybdenum billet. It is worth mentioning that the molybdenum shaft is hollow to allow water coolant to flow through it. There were two structural failures noticed in the piece; (i) a tiny portion that appeared to have melted and chipped away, and (ii) a crack that extended both up and down the length of the electrode. The whitish coloration in the bulb region, seen in Figure 1, is due to the interaction of molybdenum and the molten glass.

Since it was not mentioned (by the user) when the crack had occurred i.e. while it was submerged in the molten glass pool or when it was taken out of the pool, simulation studies were conducted to get an insight into the problem. Simulations were done for two scenarios: Case 1, a transient state while the molybdenum electrode was in the melt pool and Case 2, a transient state when the molybdenum electrode was taken out of the pool. Finite element studies were restricted to thermal and structural analysis of the molybdenum part. No consideration of the glass fluid flow or the electrical components was taken into account, partly due to the fact that no information was available from the user. This also meant that no simulation study was done to understand how a tiny molybdenum section had melted during its operation, since it is thought that the melting of the molybdenum part happened while it was in the glass bath. From Figure 1, it can be seen that the crack passes through the minute molten portion of the electrode. It is surmised that the crack resulted due to tensile stress distribution around the melt region.

This paper addresses the issue of crack formation in the molybdenum single piece GME through the help of finite element analysis using Abaqus 6.14-1. The molten molybdenum part is considered as a "hole" or lack of material with a surrounding surface temperature of that of molten molybdenum during Case 1. In Case 2, this restriction is removed as the part is out of the bath.

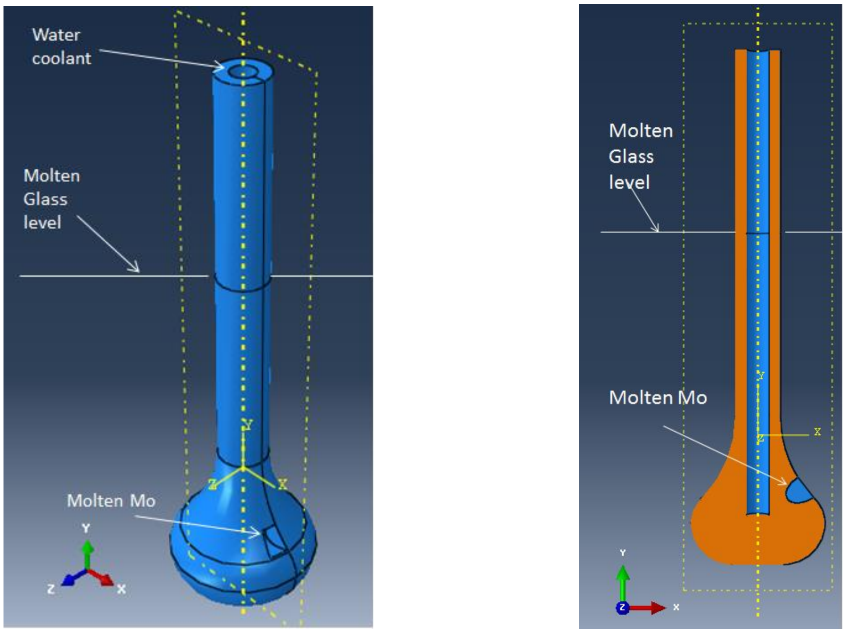
The results from the simulation for Cases 1 and 2 are described in the next section. The inferences drawn from the results are applied towards a possible design change for longer life.

Figure 1. A molybdenum single piece glass melting electrode (GME) with a molten section and a crack extending along the vertical direction of the electrode.

2. Simulation Results

A 3D model of the molybdenum electrode used in Abaqus/Standard simulation is shown in Figure 2a, and the corresponding 2D model of the part is shown in Figure 2b. As mentioned before, the internal section of the molybdenum electrode is hollow to allow convective cooling with water. All the material properties such as thermal conductivity, specific heat, thermal expansion coefficient, density, elastic constant and plastic yield stress were taken as a function of temperature. The convective water cooling aspect was modeled as a surface film condition with film coefficient of 30000 W/ m^2 °C and sink temperature of 80 °C. The element type used was C3D4T: A 4-node thermally coupled tetrahedron, linear displacement and temperature. The material property used are taken from: http://www-ferp.ucsd.edu/LIB/PROPS/PANOS/moa.html

The simulations for the two transient states (i.e., Cases 1 and 2, mentioned above) were modeled in two steps in Abaqus, and are described below.



(a) (b)

Figure 2. (a) 3D model of the molybdenum GME with a molten molybdenum section and the glass level and (b) corresponding 2D view cut.

2.1 Case 1: Molybdenum in the bath

Steady state was achieved in the material due to its use for long periods of time while submerged in the glass bath. The boundary conditions used in this particular section are shown in Figure 3. The bath temperature, molybdenum melting point, and the ambient temperature were taken as 1600 °C, 2500 °C and 50 °C, respectively, in the simulation.

The equilibrium temperature and stress distribution in the molybdenum GME after reaching steady state are shown in Figure 4. From the results of Figure 4c it can be seen that the out-of-plane stress (S33) is compressive around the molybdenum melt. Such a stress distribution is unfavorable for crack propagation along its length (see, Figure 1). This result indicates that the crack may not have originated while the molybdenum single piece GME was in the glass pool.

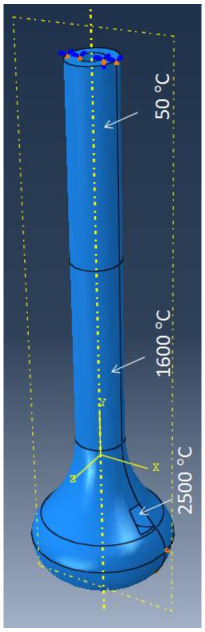
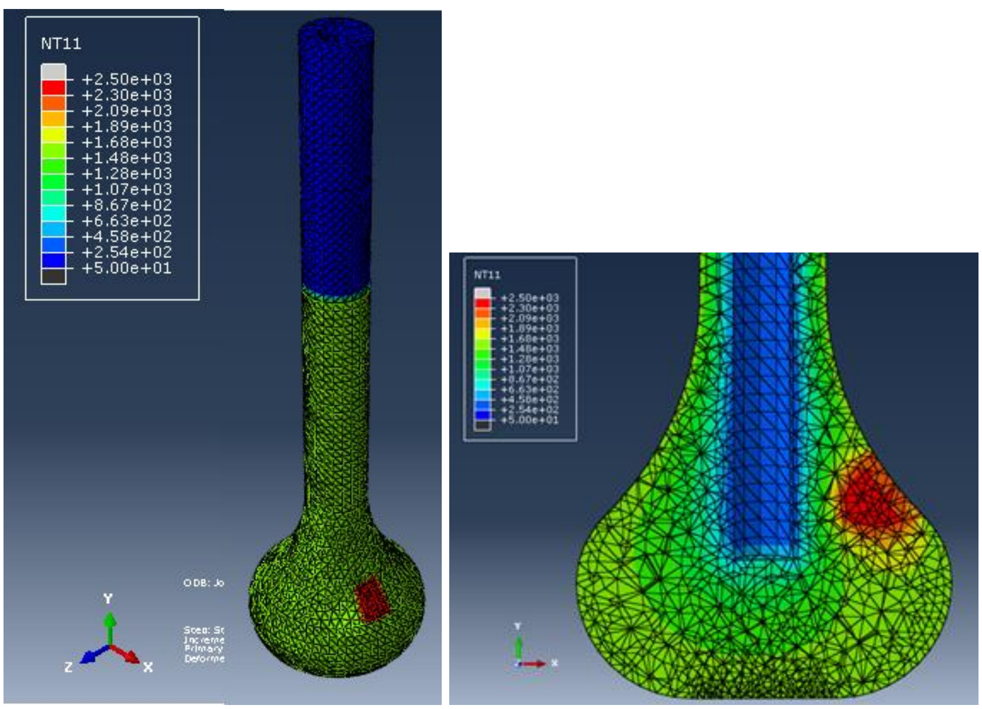
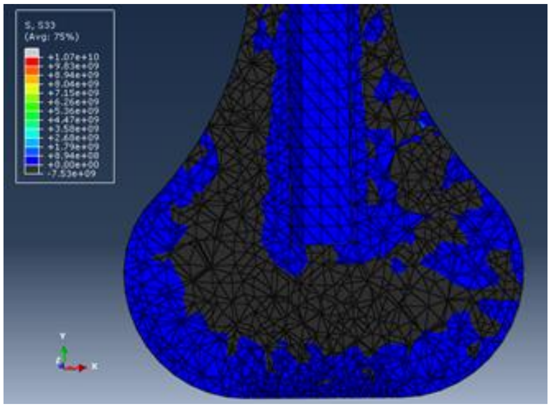


Figure 3. Temperature boundary conditions used for simulating the temperature and stresses within the molybdenum GME during Case 1.



(a) (b)



(c)

Figure 4. (a) Temperature distribution on the outside of molybdenum GME, (b) temperature distribution within molybdenum GME, and (c) normal stress distribution in out-of-plane direction. The dark regions show compressive S33 stresses. The unit for temperature is °C and stress is Pa.

2.2 Case 2: Molybdenum outside the bath

The simulation in this section assumes the molybdenum GME was taken out of the glass bath and allowed to air cool. The boundary conditions used in this section are shown in Figure 5. The convective air cooling parameters were taken as 100 W/m^2 °C (heat transfer coefficient) and 50 °C (sink temperature). Additionally, radiation was also considered with emissivity of 0.7.

Figure 6a shows the temperature distribution within the molybdenum GME after 300 sec. The corresponding S33 stress (out-of plane) is shown in Figures 6b and 6c. It can be readily seen that the stress is tensile along the length of the electrode; thereby, favoring crack propagation. Also, the tensile stress diminishes towards the bottom bulb of the molybdenum electrode. Such a stress distribution is quite close in appearance to the crack morphology shown in Figure 1.

Therefore, the analysis indicates that crack propagation may have occurred after the GME was removed from the molten glass bath.

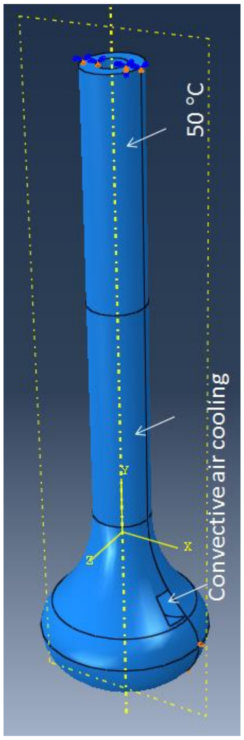
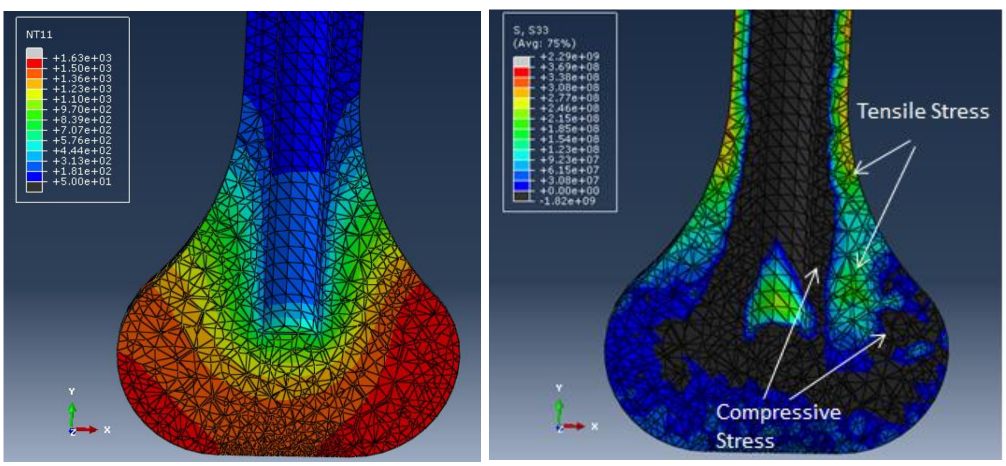


Figure 5. Temperature boundary conditions used for simulating the temperature and stresses within the molybdenum GME during Case 2.



(a) (b)

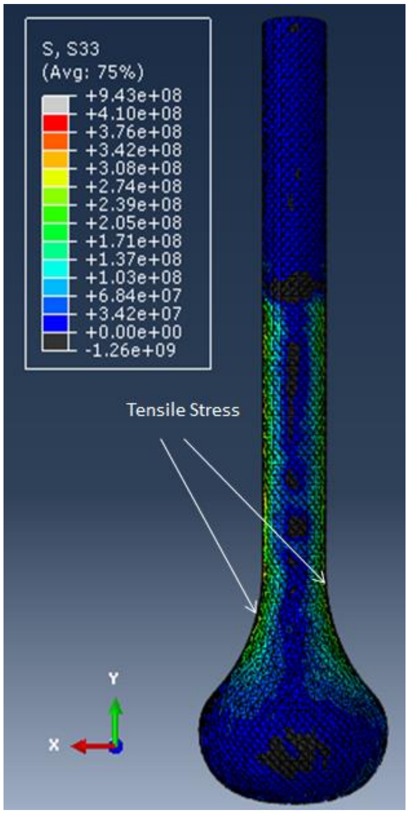


Figure 6. (a) Temperature distribution of molybdenum GME after being taken out of the glass pool, (b) normal stress distribution in out-of-plane direction, and (c) view of tensile stress in molybdenum GME. The unit for temperature is °C and stress is Pa.

3. Discussion

From the simulation results in the previous sections, it may be inferred that the narrow length of the single piece molybdenum electrode facilitates crack growth; whereas, the bottom bulb portion, due to its higher thermal mass, is able to restrict crack propagation. Therefore, a design modification to make the transition from the bulb to the stem more gradual was envisioned (Figure 7). However, this would make the GME inherently more expensive. Another solution, not related to the design, may lie in rotating the electrodes during operation in the glass bath to mitigate "hot spots" and localized melting. At present, both potential solutions are being evaluated.

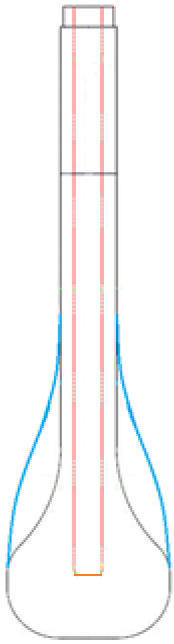


Figure 7. Proposed improved design for molybdenum GME for longer life, with the “blue” colored lines indicating a design change from the present dark lines.

5. Conclusion

Finite element analysis using Abaqus 6.14-1 was used to understand the failure mechanism in a molybdenum single piece GME. The simulation results were used to establish a plausible failure scenario and accurately predict the location of the crack in the molybdenum GME. It was found that the part most likely failed when it was taken out of the glass bath, and not while it was immersed in the molten glass. Such a study has helped in redesigning the molybdenum GME for a longer service life.

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