Simulation of Mechanical Stress on Stainless Steel for Pb-Bi Corrosion Test by Using ABAQUS

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Abstract. Pb-Bi eutectic with its advantageous is proposed to be utilized as a coolant in the GEN IV type of reactor. However, high temperature corrosion when contact with stainless steels is one of the issues of Pb-Bi eutectic utilization. It is known that in the environment of high temperature Pb-Bi, mechanical strength of stainless steel may decrease. Thus, simulation of mechanical stress working on stainless steel during in-situ bending test by using ABAQUS was conducted. Several bending degrees were simulated at high temperature to obtain the mechanical stress information. Temperature condition was strongly affect the stress vs. displacement profile. The reported mechanical strength reduction percentage was used to draw predicted mechanical stress under high temperature Pb-Bi environment.

1. Introduction
GEN IV type reactor emphasized more on safety and cost efficiency aspects. High heat capacity materials for coolant are favourable in the GEN IV reactor system to gain more energy from nuclear reaction. Lead-alloy coolant is one of the proposed coolants for the reactor. The lead-alloy coolant has several major advantageous, such as: low melting point, high boiling point, better neutron economy and chemically inert [1].

However, Pb-Bi interaction with structural material rises a corrosion issue [2]. The interaction with structural material such as stainless steel or Fe-based material depending on oxygen concentration of surrounding environment may induced oxidation or dissolution of selective element [3].

Report on cold worked materials under lead-alloy coolant show influence of stress, i.e. cold work degree, on oxide layer formation [4]. High cold work degree shows accelerate oxide scale generation and vice versa.

Only few studies regarding in situ stress under thermal load and Pb-Bi attack. Creep test under Pb environment conducted by yurechko et al. shows decrease of creep strength [5]. Low temperature punch test conducted by Ye et al. shows transformation of T91 from ductile to brittle. Bending test by Yamaki et al. focusing on coating condition [6]. Few reported works claimed minor influence of hydrodynamic effect or stress (bending) on LBE attack. However, question rises on the complete effect of stress since it may transform grain boundary (GB), i.e. elongated grain or crystallization that accelerate corrosion.

In accordance, extensive experiment to tackle that unclear understanding is important. Thus the main issue or objective is to create condition of high temperature with stress under LBE attack. For detailed understanding, variety of temperature and stress as well as oxygen concentration conditions are needed.
Thus, to support the main objective, this study is aiming to generate stress information using computational analysis software on several bending conditions as well as evaluation on stress reduction under Pb-alloy environment.

2. Simulation Method
The simulation was conducted in 2D with dimension of truncated ring using finite element analysis (FEA) method, i.e. ABAQUS code [7]. The dimension is 50 mm in diameter and 5 mm in thickness. Temperature conditions were conducted at 500, 600 and 800 °C. The materials were bended with various height reduction up to 30%. Change of the height were simulated by applying force on the top of the ring and static point on the bottom. The material was T91, where mechanical properties were reported by Scapin who conducted experiment at several temperatures [8]. The report was used as an input for ABAQUS code simulation.

Ye and Yurechko reported mechanical properties of T91 decrease during immersion in high temperature LBE [5], [9], [10]. From the reports it is known that about 10% of modulus bulk reduction occur under Pb-Bi from the same temperature at air environment. This information was used to conducted prediction simulation of T91 behavior under tension in high temperature LBE.

![Figure 1. schematic figure of material testing in 2D.](image)

3. Results and Discussions
The simulation were conducted at three temperature conditions of 500, 600 and 800 °C. Stress profiles were evaluated with height reduction up to 30% under open air condition. Typical results of stress investigation using ABAQUS program are shown in figures 2 to 4.

Figure 2 shows result of stress profile of T91 at 500°C with height reduction of about 30% from initial height. It can be seen that stress is concentrated in the middle area of the truncated ring. However, the near surface of inner-middle ring exhibited slightly lower stress in comparison to inner bulk of middle area. The highest stress is at the inner bulk of the middle area and extend to side area. The highest stress calculated is about 418.86 MPa. The blue region is the less affected area by bending mechanism. The outer surface of middle part of the ring also shows high stress.
Figure 2. Stress profile of T91 at 500°C with height reduction of about 30%.

Figure 3 shows stress profile of T91 at 600°C with height reduction of about 30%. At this temperature, high stress concentrated in the bulk at middle area of the truncated ring. However, unlike at temperature 500°C, the high stress is not overly extended to the side area. After height reduction of 30% of initial condition, maximum stress recorded is about 242.66 MPa. However, the near surface of inner part of the ring shows stress of about 141.71 MPa.

Figure 3. Stress profile of T91 at 600°C with height reduction of about 30%.

Figure 4 shows stress profile of T91 at 800°C. At this temperature, high stress spreads in the near-surface of the middle ring (inner and outer). This was different mechanism in comparison with two previous temperature conditions. Plastic deformation seems to occur at the inner and outer surface of the ring. It shows that increase of temperature condition highly influenced stress spreading profile.
Figure 4. Stress profile of T91 at 800°C with height reduction of about 30%.

Figure 5 presents graph of stress versus displacement of T91 at 500, 600 and 800°C. The graph was the profile of an outer surface mesh at the middle of the ring. Temperature condition was strongly affect maximum stress of the T91. At 500°C, elastic deformation presents only up to 1.5 mm of displacement. The maximum load at this temperature is about 432 MPa. Stress then decreasing gradually. Similarly, at 600°C, elastic deformation occurs up to about 1.5 mm of displacement. The maximum load is about 267 MPa after 2.9 mm of displacement. This temperature roughly has similar trend with test at 500°C, material become soft whenever height reduction continue. On the other hand, at 800°C, after elastic range hardening mechanism occur.

Figure 5. Stress vs. displacement profile of T91 at 500, 600 & 800°C.

Stress vs. displacement profiles under LBE environment are shown in figure 6. Calculations were made by reducing the value in fig.5 by 10%. It is reported that mechanical strength of material decreases of about 10% when testing under Pb-Bi environment [5], [9]. At 500 and 600°C, maximum load in Pb-Bi environment are about 390 and 240 MPa, respectively. After then, softening of the T91 occurred. At 800°C, elastic zone occurs before 49 MPa. After then, hardening occurs while height reduction continue.
This data will be valuable for correlating of corrosion behavior with stress on the material. The future experiment of our group will be corrosion test of stainless steel under Pb-alloy with variety stress profiles.

4. Conclusions
Simulation of bending test of T91 at several temperatures was successfully conducted. Two dimensional truncated ring was used as geometry for the simulation. Stress vs. displacement profiles were generated using previous reported data as input file. Temperature condition at 500 and 600 C show similar trend of softening mechanism, while at 800 C, hardening mechanism was observed. Prediction of stress profile under Pb-Bi were conducted by using simple correlation from previous reports.

5. Acknowledgments
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