Material Degradation Testing and Analysis for Next Generation CSP Applications

Stuart Bell[1], Madjid Sarvghad Moghaddam[1], Teng Cheong Ong[1], Richard Clegg, Geoff Will[1] and Ted Steinberg[1]

[1]*School of Mechanical, Medical and Process Engineering, Science and Engineering Faculty, Queensland University of Technology*
2 George St, Brisbane City QLD 4000

Structural materials used for next generation concentrating solar power (CSP) applications have significant challenges in order to meet the life requirements of these plants. High operational temperatures, corrosive environments and transient thermal and stress conditions can cause several issues which contribute to reducing material life via a number of damage mechanisms. Identifying and understanding these mechanisms has been the major focus of the Australian Solar Thermal Research Institute (ASTRI) Advanced Materials group to better inform materials selection and life prediction for CSP applications.

Introduction

The ASTRI Advanced Materials group has been working to support ASTRI goals by analysing degradation mechanisms in structural materials. To date this has included analysis of molten salt properties, corrosion in molten salt, corrosion in supercritical CO_2, failure analysis and materials selection. Future avenues for investigation being developed by the Advanced Materials group include corrosion/degradation and flow/erosion in liquid sodium; the effect of molten salt and sodium on mechanical properties such as fatigue and creep life; the combination of stress and corrosion and its' effect on mechanical strength; the effect of welds on corrosion and strength under CSP conditions; and the degradation of material strength from phase changes due to transient thermal conditions.

Molten Salt Corrosion and Properties

The Advanced Materials group at QUT a developed a strong platform in corrosion, particularly molten salt corrosion for solar thermal applications. The group has focussed identifying degradation mechanisms via experimental studies based on immersion of coupon in corrosive media.

The work done here identified a number of mechanisms and effects of molten salts on structural metals. Depletion of major alloying elements, often chromium, from the surface of the alloy to significant depths of hundreds of microns has been identified in 601 nickel alloy with a chloride/carbonate salt [1]. This process appeared to be uninhibited by corrosion layers on the surface, or by solid state diffusion as the alloy developed porosity into which the salt penetrated resulting in close contact between un-depleted metal and liquid salt. Other damage mechanisms identified by the Advanced Materials group include intergranular attack on 316 and 2205 stainless steel alloys and sulphidation in Inconel 601 alloy with a chloride/sulphate based salt [2, 3]; stress oxidative failure of Inconel 601 in a ternary carbonate salt [4];

Combined Stress and Corrosion

The potential for stress to increase corrosion rate is not often accounted for in molten salt corrosion literature, due to the difficulty in inducing known stresses in test coupons. The advanced materials group have investigated many ways in which to produce static stresses and analyse how this stress affects the corrosion rate, formation of corrosion layers and if these corrosion layers are protective. One of these tests showed that stress caused increased corrosion and degradation in 304 stainless steel alloy [5]. Further refinement of this approach is currently ongoing.

Environmental effect on Creep and Fatigue

CSP plants subjected to static and transient stresses to due varying load and thermal conditions will potentially experience creep and fatigue. These effects coupled with the surface damage which can be induced by corrosive environments could significantly reduce plant life. Even relatively small corrosion and depletion layers can take orders of magnitude off the fatigue life of components [6]. Creep and fatigue life are very sensitive to the state of the surface layer, as this is where the cracks and voids which produce a failure are principally developed. Previous research has indicated that in conditions which resist the development of surface defects, creep and fatigue life remains unaffected and even be extended significantly [7-9]. The development of methods to test the effect of next generation CSP environments on creep and fatigue life, is one of the major new directions for the Advanced Materials group.

Corrosion/Degradation in Liquid Sodium

Liquid sodium is a heat transfer fluid of great interest to CSP. Structural metals exposed to liquid sodium at elevated temperatures can cause surface damage in several ways, such as de-alloying of elements and carburisation/de-carburisation. These pathways are very dependant upon the conditions of the system, particularly oxygen and carbon concentration in the sodium, and temperature. Additionally, liquid metal embrittlement of structural metals by sodium has the potential to cause catastrophic failure with little warning. Liquid metal embrittlement at low temperatures which may occur overnight in receiver and piping, is of major concern in CSP systems.

The Advanced Materials group is developing its capabilities in working with and testing in liquid sodium. From immersion-based testing for corrosion and microstructural analysis; flowing sodium testing to determine erosion/corrosion and deposition behaviour (particularly when temperature gradients are present); to mechanical loading tests for strength, fatigue, and creep characteristics to sodium exposed samples.

Phase changes due to Transient Thermal Conditions

The high temperatures, in conjunction with thermal cycles could produce changes to the phases present in structural alloys – independent of the surface exposure. The development of deleterious phases such as sigma and delta phases, could significantly reduce the strength of these alloys in CSP applications. The Advanced Materials group plans to develop models to account for these effects and establish operational limits based upon the thermal degradation mechanisms inherent in the materials.

Conclusion

Understanding how structural materials respond to, and are degraded by, the conditions they experience in CSP plants is critical to prevent performance degradation and failure. The high temperatures and corrosive environments which next generation CSP plants demand add to the challenge of materials selection and life prediction. The ASTRI Advanced materials group are strongly situated to investigate the mechanisms and pathways of materials' degradation, and provide information and test data to support materials selection and life prediction to the CSP community.

[1] Bell, S., K. Lippiatt, T. Steinberg, and G. Will, 2019, 'Damage analysis of 601 nickel superalloy in eutectic Na2CO3/NaCl molten salt under isothermal and thermal cycling conditions,' *Solar Energy,* Volume 191, p637-646.
[2] Sarvghad, M., G. Will, and T. A. Steinberg, 2017, 'Corrosion of Inconel 601 in molten salts for thermal energy storage,' *Solar Energy Materials and Solar Cells,* Volume 172, p220-229.
[3] Sarvghad, M., G. Will, and T. A. Steinberg, 2018, 'Corrosion of steel alloys in molten NaCl + Na2SO4 at 700°C for thermal energy storage,' *Solar Energy Materials and Solar Cells,* Volume 179, p207-216.
[4] Sarvghad, M., S. Bell, R. Raud, T. A. Steinberg, and G. Will, 2017, 'Stress assisted oxidative failure of Inconel 601 for thermal energy storage,' *Solar Energy Materials and Solar Cells,* Volume 159, p510-517.
[5] Bell, S., D. Stoker, G. Will, and T. Steinberg, 2019, 'Effects of mechanical stress on high temperature corrosion in molten salt,' presented at the SolarPACES, Casablanca, Morocco.
[6] Lewis, D. T. S., R. G. Ding, M. T. Whittaker, P. M. Mignanelli, and M. C. Hardy, 2020, 'The effect of oxidising thermal exposures on the fatigue properties of a polycrystalline powder metallurgy nickel-based superalloy,' *Materials & Design,* Volume 189, p108529.
[7] Borgstedt, H. U., 2008, 'Influence of Liquid Sodium on Mechanical Properties of Stees, Refractory Alloys and Ceramics,' in *Materials Issues for Generation IV Systems. NATO Science for Peace and Security Series B: Physics and Biophysics*, G. D. Ghetta V., Mazière D., Pontikis V., Ed., ed Dordrecht: Springer.
[8] Natesan, K., M. Li, O. K. Chopra, and S. Majumdar, 2009, 'Sodium effects on mechanical performance and consideration in high temperature structural design for advanced reactors,' *Journal of Nuclear Materials,* Volume 392, p243-248.
[9] Anantatmula, R. P. and E. R. Gilbert, 1980, 'In-sodium creep behavior of alloys M-813 and Nimonic PE16,' presented at the International conference of liquid metal technology for energy systems, Richland, WA, USA.