Tribology International 123 (2018) 372–384

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

# Elevated temperature tribology of Ni alloys under helium environment for nuclear reactor applications

Md Saifur Rahman[a], Jie Ding[b], Ali Beheshti[c], Xinghang Zhang[b], Andreas A. Polycarpou[a,*]

[a] Department of Mechanical Engineering, Texas A&M University, College Station, TX, 77843, USA
[b] School of Materials Engineering, Purdue University, West Lafayette, IN, 47907, USA
[c] Department of Mechanical Engineering, George Mason University, Fairfax, VA, 22030, USA

ARTICLE INFO

*Keywords:*
Nuclear reactor
Elevated temperature helium tribology
Inconel 617
Alloy 800HT

ABSTRACT

The current study investigates the friction and wear behavior of two primary candidate materials, Inconel 617 and alloy 800HT for high-temperature gas cooled nuclear reactors/very-high-temperature reactors. Using a custom-built high temperature tribometer, helium cooled reactor environment was simulated at room and 800 °C temperatures. Microscopy and chemical analyses were carried out to explain the tribological performance of the alloys. At elevated temperatures, both alloys show higher friction in helium, compared to air environment. Both alloys exhibit high wear resistance in all experimental conditions, except at high temperature helium environment. The formation of glazed and mechanically mixed layers of oxides were found to be important causes for the lower friction and wear in high temperature air atmosphere.

## 1. Introduction

A very-high-temperature reactor (VHTR) and a high-temperature gas-cooled reactor (HTGR), are Generation IV nuclear reactor concepts for the economical production of electricity and hydrogen. Operating at high temperature (HT) is critical for nuclear reactors as it results in substantial thermal efficiency improvement. Therefore, in view of the design demands, materials that can withstand HT, as well as harsh environments, are deemed necessary for reliable and effective nuclear reactor operation. The combination of very HT operation with 60 years of intended license period restricts material options to a small number of course-grained solid-solution strengthened alloys that can provide stability, creep resistance and environmental resistance. Nickel based alloy 800HT and Inconel 617 are the principal candidates for HTGR/VHTRs reactors with outlet temperatures of 700–950 °C which should be licensed for a 60-year life [1–3]. Of course, not all of the designed components can be targeted for such a long period of time; nonetheless, time intervals between two replacements should be sufficiently long and more importantly lifetime must be estimated as accurate as possible. Thus, there is no surprise that significant efforts have been made to characterize the behaviors of these nickel alloys. The literature is relatively abundant with works pertaining to mechanical behavior studies (mostly fatigue, fracture, and creep) [4–8] as well as oxidation and corrosion [2,3,9–14], for 800HT, Inconel 617 and other nickel alloys. Yet, tribological studies of alloy 800HT and Inconel 617 interfaces are limited [15,16].

Sliding motion and its consequent friction and wear between metallic components at elevated temperatures can lead to severe surface damage and are important considerations for the effective performance of moving parts in nuclear reactors and power generation components. HT tribology is challenging on its own, and in the case of nuclear reactor conditions, the complexity is further compounded by the fact that the interface between metallic surfaces at HT remains non-lubricated with low water or oxygen partial pressure in the presence of Helium (He) and other minor gaseous ingredients. Tribo-pairs in the HTGR/VHTR include valves, valve seats, valve shafts, He circulator shafts and bearings, as well as control rods where for rubbing surfaces, accelerated friction and surface damage can have significant detrimental effects on component performance and life.

One of the most significant factors controlling metals' tribological behavior under HT conditions is oxidation. Generally, HT alloys are thermodynamically unstable and react with oxygen to form oxides in air. The oxidation behavior of Inconel 617 is reported to be similar in air and He environments with Cr rich oxides on the surface [10,11,13]. In fact, the slow-growing oxide scale on the surface provides protection from further oxidation where the rate of oxidation is controlled by the diffusion of the reactants through the oxide scale. The stability of the Cr rich oxide scale depends on the oxygen and carbon monoxide partial pressures controlling steady-state reaction kinetics in He environment, which is essential to avoid decarburization of alloys in reactors [2,3,9].

* Corresponding author.
*E-mail address:* aploycarpou@tamu.edu (A.A. Polycarpou).

https://doi.org/10.1016/j.triboint.2018.03.021
Received 11 December 2017; Received in revised form 14 March 2018; Accepted 20 March 2018
Available online 23 March 2018
0301-679X/ 

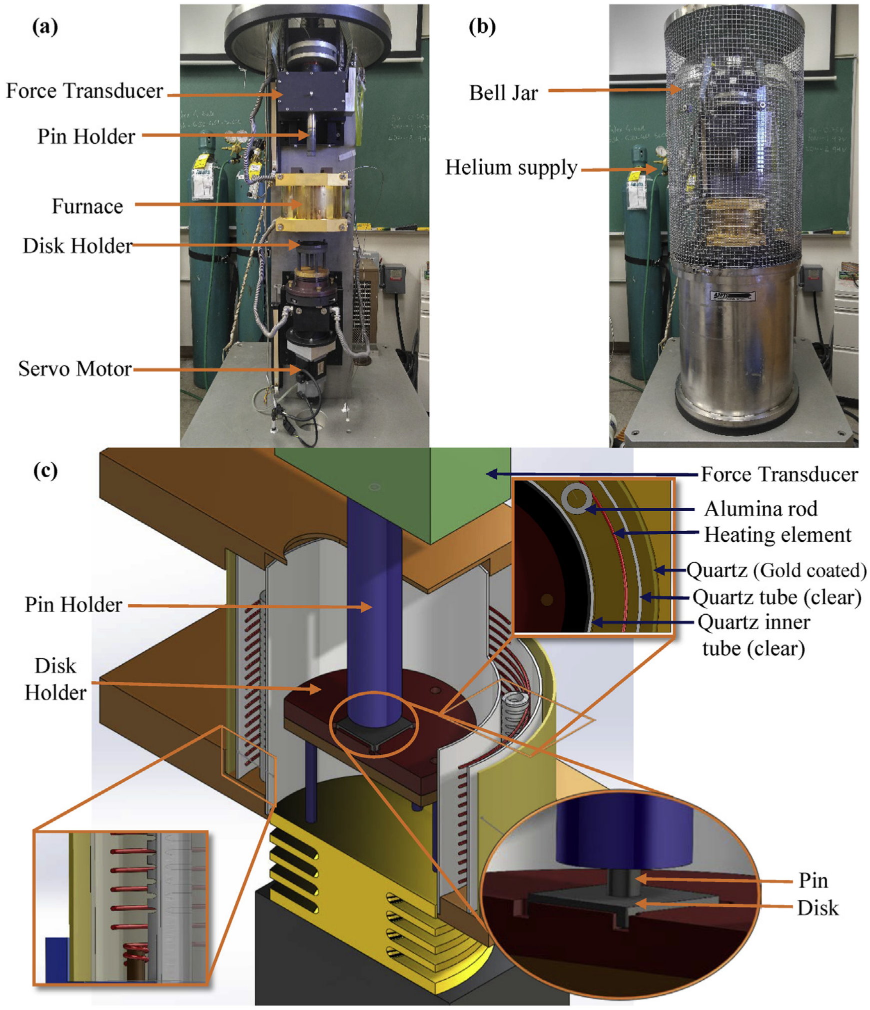


**Fig. 1.** High temperature tribometer (a) Tribometer setup, (b) Bell jar chamber for vacuum and controlled environment, (c) Furnace construction.

**Table 1**
Chemical composition of Inconel 617 and 800HT (in wt%).

| **Element** | **C** | **Mn** | **Fe** | **S** | **Si** | **Cu** | **Ni** |
|---|---|---|---|---|---|---|---|
| Inc 617 | 0.08 | 0.23 | 1.46 | 0.001 | 0.2 | 0.02 | 53.27 |
| | **Cr** | **Al** | **Ti** | **Co** | **Mo** | **P** | **B** |
| | 22.02 | 1.10 | 0.32 | 11.91 | 9.38 | 0.005 | 0.002 |
| 800HT | **C** | **Mn** | **Fe** | **S** | **Si** | **Cu** | **Ni** |
| | 0.061 | 1.27 | 46.24 | 0.001 | 0.42 | 0.2 | 30.65 |
| | **Cr** | **Al** | **Ti** | **Co** | **Mo** | **P** | **B** |
| | 19.7 | 0.56 | 0.54 | 0.1 | - | 0.024 | - |

**Table 2**
Composition of impurities in He (in ppm by volume) [2,3].

| | He | $O_2$ | $H_2O$ | $CH_4$ | CO | $CO_2$ | $H_2$ | $N_2$ |
|---|---|---|---|---|---|---|---|---|
| Present research | Bal. | 1 | 1 | 0.5 | 1 | 1 | – | 5 |
| Dragon | Bal. | 0.1 | 0.1 | 0.1 | 0.05 | 0.02 | 0.1 | 0.05 |
| Peach Bottom | Bal. | – | 0.5 | 1 | 0.5 | < 0.05 | 10 | 0.5 |
| Fort St. Vrain | Bal. | – | 1 | 0.1 | 3 | 1 | 7 | – |
| AVR | Bal. | – | 0.15 | 1 | 45 | 0.25 | 9 | 22 |
| THTR | Bal. | – | < 0.01 | 0.1 | 0.4 | 0.2 | 0.8 | 0.1 |

**Table 3**
Experimental conditions.

| Disk | Pin | Ambient | Temperature (°C) | Normal Force (N) | Sliding velocity (m/s) |
|---|---|---|---|---|---|
| Inc 617<br>800HT | Inc 617<br>800HT | Air, He | 25, 800<br>25, 750 | 5 | 0.04 |

**Table 4**
Protocol for HTT experiments with He flow.

| Time (min) | State | He volume flow rate (l/min) | Relative Pressure (psi) |
|---|---|---|---|
| 0 | Initial condition | 0 | 0 |
| 1–5 | Test chamber vacuumed | 0 | −14.0 ~ −14.3 |
| 6–15 | He flushed the test chamber | ~25 | 0.1 ± 0.02 |
| 16–45 | Vacuum and flushing of He (Two times) | ~25 | −14.3 ± 0.1 |
| 46–55 | Create positive pressure and execute test | ~60 (Full Open) | 0.1 ± 0.05 |
| 56–85 | Heating chamber to desired temperature | 5–10 | 0.1 ± 0.02 |
| 86–95 | Conduct experiment | 5–10 | 0.1 ± 0.02 |
| 96–185 | Cooling down | 5–10 | 0.15 ± 0.02 |