Development of alumina-forming Ni-base alloys as structural materials of molten salt reactors

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1. Introduction

Molten salt reactors (MSRs) have become interested again as an alternative to coal-fired power plants for reducing carbon emissions. Operating at atmospheric pressure, MSRs inherently prevent severe accidents. However, the highly corrosive nature of molten salt results in a significant challenge to MSR operations. In the 1960s, Oak Ridge National Laboratory (ORNL) developed Hastelloy N as a structural material for MSRs to adress the corrosion concerns. Nonetheless, MSR operations with Hastelloy N were stopped due to irradiation embrittlement [1].

Recent KAERI research focuses on MSR utilizing chloride salts. While chloride salts exhibit faster corrosion behavior [2], more fuel can be loaded compared to fluoride salts. Additionally, recent findings showed alumina is stable in molten chloride salts [3]. As a response, we designed new Ni-base alloys with high Al content to enhance corrosion resistance in chloride salts. The preliminary results of new alloys on the performance of these new alloys will be presented including mechanical properties and corrosion behavior in molten salt.

2. Materials and Experimental procedure

Initial alloy design aimed for a single FCC phase with γ'-Ni_3Al where the Al-rich precipitates contribute to high-temperature strengthening. Using Thermo-Calc with the TCNI-8 database, preliminary chemical compositions of the new alloys were determined. Based on the thermodynamic calculations, several alloys were prepared by vacuum induction melting (VIM). Ingots were hot-rolled at 1000-1250°C with an 80% thickness reduction, followed by annealing.

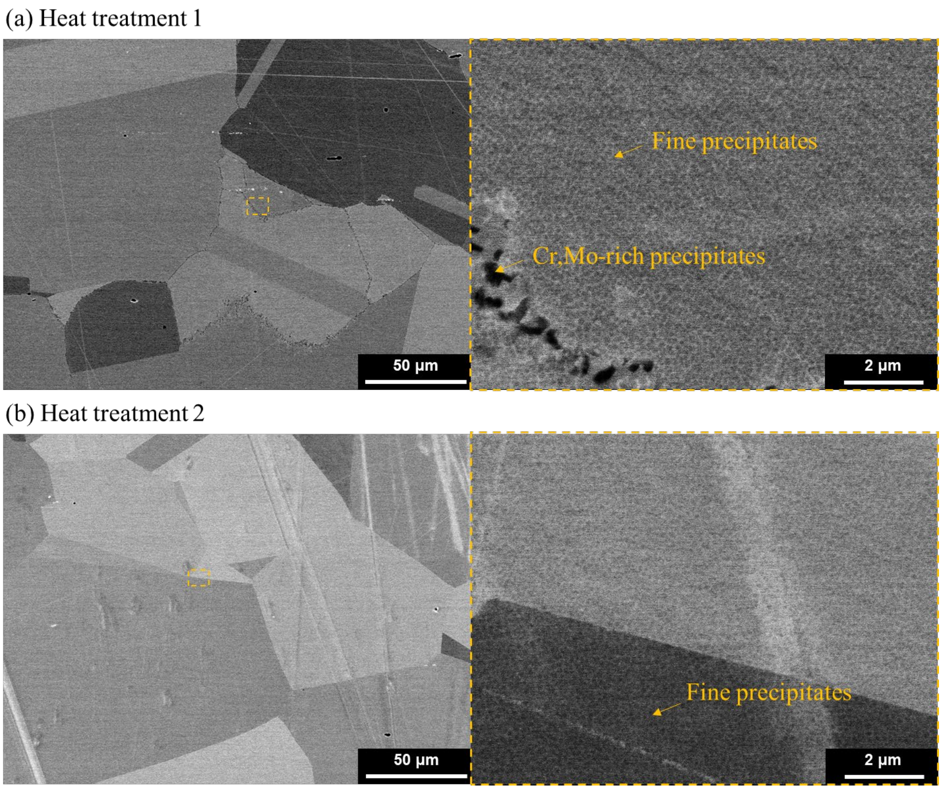

Figure 1. Microstructure of high-Al-containing Ni-base alloys with different heat treatment

For tensile testing, hot-rolled and annealed plates were fabricated into plate-type specimens with a gauge length of 15 mm, a width of 3 mm, and a thickness of 1 mm by electrical discharge machining (EDM). Tensile testing was performed at both RT and 700°C. Prior to tensile testing at 700°C, specimens were placed at the target temperature for at least 5 min.

For molten salt corrosion testing, 57mol%NaCl-43mol%$MgCl_2$ was prepared in an Ar-filled glove box. Because $MgCl_2$ is easily combined with moisture, the mixed salts are purified before the corrosion testing. The mixed salt powder was heat-treated at 300°C for 24 h, then was kept at 600°C for 48 h with Mg pellets. At least two specimens for each alloy were hung with an alumina rod in the individual alumina crucible to avoid galvanic corrosion then, the purified salts were introduced into the crucibles at RT in the Ar-filled glove box. Finally, the crucibles were heated to 700°C in the furnace in the Ar-filled glove box, then the temperature was kept for 200 h. Following the corrosion testing, the salts on the specimens were carefully removed with distilled water.

3. Results

Figure 2 shows the microstructure of the newly developed Ni-base alloys with different heat treatments. All heat treatment conditions presented an austenite matrix with very fine nano-sized Al-rich precipitates. While the grain size for both conditions looked similar, the heat treatment 1 condition exhibited Cr,Mo-rich precipitates at the grain boundaries.

To check the tensile properties of the new alloys, tensile testing was carried out with different chemical compositions at RT, and with a selected condition at 700°C, and results are shown in **Figure 2**. Thanks to the ductile austenite and fine precipitates in the microstructure, all compositions exhibited a pretty high yield strength of 700~900 MPa and reasonable elongation of 20~30 %. The high yield strength of approximately 550 MPa was also presented even at 700°C, which is much higher than the strength of Hastelloy N at 700°C (about 200 MPa).

To compare the corrosion resistance with Hastelloy N, Hastelloy N also was fabricated into rectangular specimens, and tested with the same procedure. Before and after the corrosion testing at 700°C for 200 h, each specimen was weighed, and the weight change results are shown in **Figure 3**. The three conditions, A to C, had the same chemical composition and different thermomechanical processing (TMPs). The tested alloys showed weight loss behavior except the condition A. Comparing Hastelloy N, condition C showed similar weight loss behavior and condition B exhibited slightly less weight loss. It is implied that the corrosion behavior in molten salt for high Al-containing Ni-base alloys highly depends on their microstructures even if they have the same chemical composition.

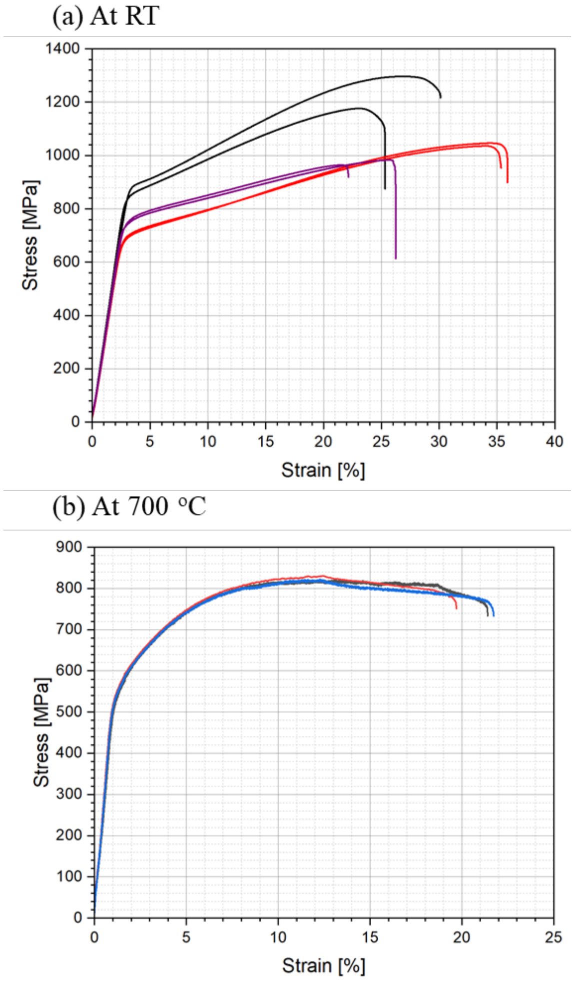

Figure 2. Tensile test results of high-Al-containing Ni-base alloys at (a) RT and (b) 700°C.

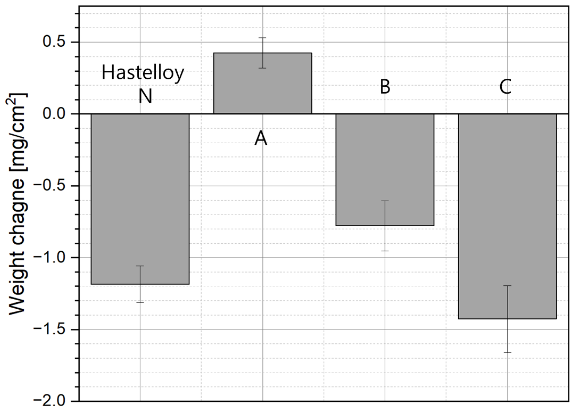

Figure 3. Weight changes of Hastelloy N and newly-developed alloys with different heat treatments after NaCl-$MgCl_2$ corrosion testing at 700°C for 200 h.

4. Summary and Future works

High-Al-containing Ni-base alloys were newly developed for structural materials of molten salt reactors. The new alloys have a very high Al content of above 5 wt.% to produce a protective layer in the corrosive molten salts. Because of Al-rich fine precipitates, Such Al let the alloys have high strength as well as good corrosion resistance. Meanwhile, different corrosion behavior was observed with different microstructures. In the conference, the detailed relation between microstructure and the corrosion behavior will be dealt with.

REFERENCES

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