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ANNEALING STUDIES ON FeCrAl FUEL CLADDING

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INTRODUCTION

Following the Fukushima nuclear accident in 2011, there has been a tremendous interest in developing accident tolerant fuel (ATF) materials, including new cladding materials that can improve or replace the traditional Zircaloys in light water reactors (LWRs). The anticipated benefits of ATFs include enhanced accident response while offering improved performance.

Among the several ATF clad designs, coatings, SiC-SiC composites, and FeCrAl are actively pursued by the industry and the national laboratories. FeCrAl alloys belong to a class of iron-based alloys developed more than 40 years ago; they are primarily used as heating elements and components at high temperatures due to their superior oxidation resistance (Terrani, 2018). Chromium and aluminum provide resistance to corrosion, stress-corrosion cracking, radiation-induced swelling, and high-temperature oxidation. FeCrAl alloys form oxide layers at the surface, which protect the cladding from severe chemical attacks even at relatively high temperatures (Yamamoto et al., 2017).

Several studies have been carried out in the past to investigate the stability of low chromium-containing FeCrAl alloys (Maji et al., 2021, Liu and Wenbo, 2021, and Tuo et. al., 2022). Different techniques such as hot extrusion and warm pilgering, and several alloying methods have been reported previously (Qin et al., 2022). Currently, the microstructural stability of high chromium-containing FeCrAl alloys is not well-elucidated. For example, the existence of laves phases and the tendency of chromium to segregate into α' phase requires more detailed microstructural characterization (Yamamoto et. al., 2019).

EXPERIMENTAL

Kanthal APMT alloy is a commercial version of FeCrAl Alloy made by Kanthal from Sweden; the chemical composition of Kanthal APMT is listed in Table 1. Samples are annealed in an argon environment inside a three-zone ATS furnace, and temperature is measured using two k-type thermocouples attached to the samples along with the built-in thermocouples of the furnace. The temperature change during annealing tests is bounded within ± 1°C. Tensile tests are performed using a universal tensile test machine from Instron Corporation.

Table 1: Representative chemical composition (%) of Kanthal APMT FeCrAl alloy.

C	0.08
Si	0.7
Mn	0.4
Mo	3.0
Cr	21.0
Al	5.0
Fe	Balance

RESULTS

Figure 1 shows the change in the ultimate tensile strength (UTS) and yield strength (panel a), and ductility and uniform strain (panel b) of FeCrAl APMT alloy following four different annealing times at 700°C. As expected, the strength decreases when annealing time is increased from four to five hours but exhibits an increase with longer annealing times. The softening can arise due to the recrystallization and grain growth while the subsequent hardening can be attributed to coarsening of precipitates, and agglomeration of laves phases. Similarly, ductility follows the changes in strength with an initial increase followed by a significant decrease.

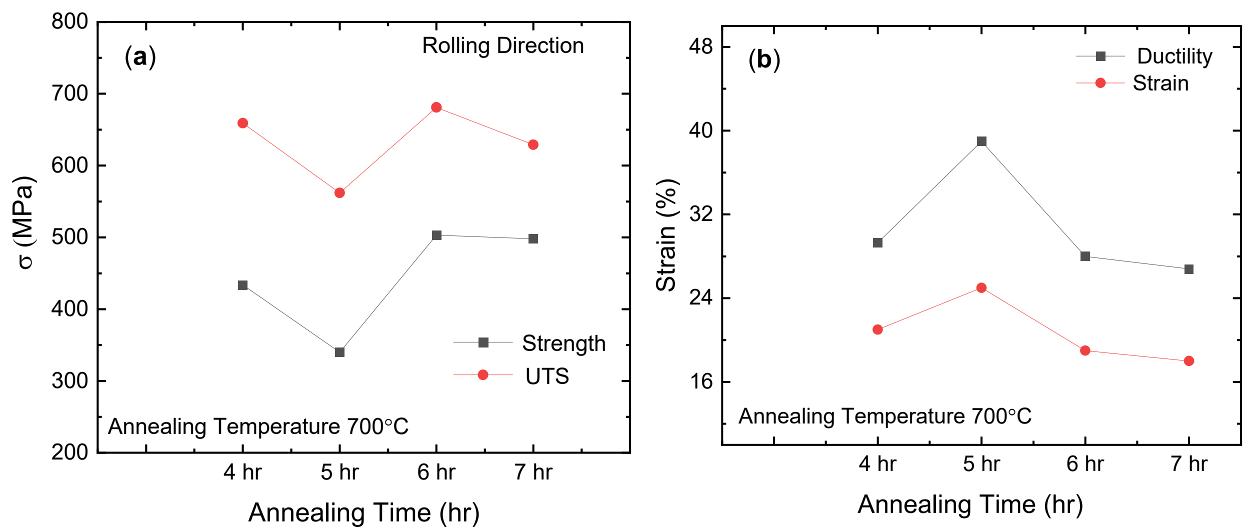

Figure 1. Effect of annealing time on (a) the mechanical strength, and (b) ductility of FeCrAl APMT alloy at 700°C. The yield strength and UTS of the as-received samples without annealing are 570 MPa and 719 MPa, respectively, corresponding to 29% ductility and 19% strain, respectively.

Figure 2(a) shows a continuous softening behavior along the transverse direction with an increase in the annealing temperature. Recrystallization, and changes in precipitate structure and laves phase are possible reasons for the decrease in the UTS values. As shown in Figure 2(b), the decrease in the UTS is larger (27%) along the rolling direction relative to the transverse direction (14%) across the range of temperatures tested (from 600°C to 800°C). Microstructure characterization on the tested samples is in progress to identify the plausible deformation mechanisms.

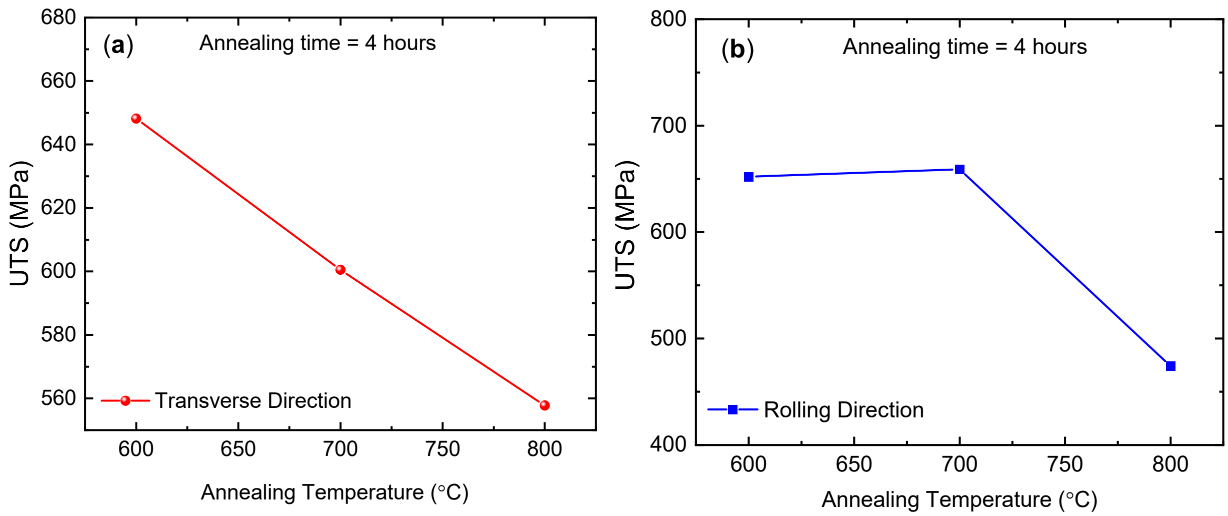

Figure 2. Effect of ultimate tensile strength (UTS) on annealing temperature (a) along the transverse direction, and (b) along the rolling direction. The annealing time is 4 hours.

CONCLUSION

Annealing studies are performed on a commercial version of FeCrAl developed by Kanthal. Tests are carried out at three different annealing temperatures (600°C, 700°C, and 800°C) for different annealing times (4 to 7 hours). A softening behavior is observed with increasing annealing temperature, which can possibly be attributed to recrystallization or microstructural changes related to inclusions. At 700℃, a crossover from softening to hardening is seen for the tensile properties at 4 hours. Further testing and microstructural characterization studies are underway to probe the mechanisms that govern the high temperature mechanical behavior.

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