# Effect of an Annealing on the Mechanical and Corrosion Properties of a HANA-4 Strip

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## 1. Introduction

As a high burn-up fuel cladding material HANA(High performance Alloy for Nuclear Application) has been developed by the Korea Atomic Energy Research Institute, recently. A series of out-of-pile and in-pile tests demonstrated that the HANA cladding tubes were superior to a commercial zirconium-base alloy in the mechanical properties as well as the corrosion properties [1,2]. Along with the research for a fuel cladding application using HANA alloys, their application to a spacer grid for a fuel assembly is also being investigated.

For robust mechanical properties of a spacer grid, an appropriate microstructure is needed. Especially, a recrystallized microstructure is desirable for proper mechanical properties, a corrosion resistance, a creep resistance, and a low irradiation growth [3]. In addition, an intermediate recrystallization is utilized to restore a ductility after a cold deformation process during a manufacturing. The recrystallization can be easily achieved when the alloy was heat-treated at high temperatures; however, an undesirable second phase particles could be formed which deteriorate corrosion resistance of the alloy. In that sense, the annealing temperatures should be controlled within proper ranges.

In this paper, the HANA-4 strip was manufactured at various annealing temperatures, and examined for the temperature which has not been considered to be desirable for its properties. It is suggested from this work that the higher temperature would also be applicable to the manufacturing. The effect of the annealing will be discussed in view of the proper mechanical and corrosion properties.

## 2. Methods and Results

The nominal chemical composition of the HANA-4 strip is Zr-1.5Nb-0.4Sn-0.2Fe-0.1Cr. The designated amounts of the solute atoms of Nb, Sn, Fe, Cr were added to a pure sponge zirconium. For homogenizing of the alloying elements, several meltings and betatizing at 1020°C for 15 min were introduced. The prepared ingots were hot-rolled and cold-rolled to have 0.66 mm thicknesses. The cold-rolling process consisted of three steps: 1st cold-roll of 35% reduction, 2nd cold-roll of 40% reduction, and final cold-roll with 65% reduction. The heat-treatments subsequent to every cold-rolling were conducted below and/or above a monotectoid temperature of about 600°C.

For the comparison, an intermediate annealing after 2nd cold-rolling was done at 600°C for 2 h or 620°C for 1 h, and final cold-rolled strips were heat-treated at 580, 600, and 620°C for 1 h. The cold-rolling and annealing conditions are presented in Table 1. For the heat-treatment, oxidation of the samples was prevented by using a quartz tubing with a vacuum. The heat-treated samples were tensile tested at room temperature in accordance with the ASTM B352 and E8. The strain rate was 0.0625 mm/mm/min through a 0.2% offset yield stress and 0.625 mm/mm/min after a yield stress. The corrosion behaviors of the samples were investigated in a 400°C steam environment and a 70 ppm of a LiOH solution in a manner consistent with the ASTM G2. For a reference, a commercial grade of the ZA outer strip was used.

Table I: Annealing conditions for the HANA-4 strip

| Sample ID | Cold-rolling and Annealing | | |
|---|---|---|---|
| | 1st (35%) | 2nd (40%) | 3rd (65%) |
| H4B | 570x3h | 600x2h | 600x1h |
| H4D | | 620x1h | 580x1h |
| H4E | | | 600x1h |
| H4F | | | 620x1h |

### *2.1 Tensile Properties*

Figure 1 shows the tensile properties of the manufactured HANA-4 strip, i.e. H4B, H4D, H4E, and H4F, with respect to the different heat-treatment temperatures. The red and blue lines in Fig. 1 show the ultimate tensile strength (UTS) and yield strength (YS) of reference values of the ZA strip.

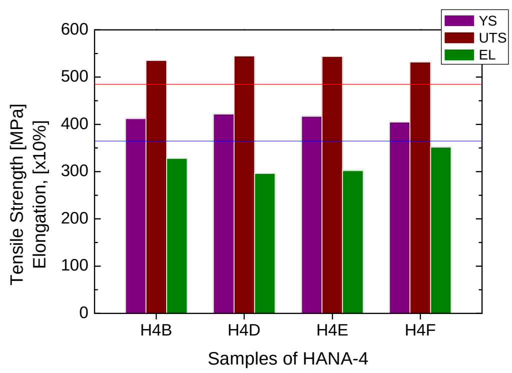


Fig. 1. Tensile mechanical strengths for the HANA-4 strips annealed at various temperatures.

The yield stress and ultimate tensile stress of the manufactured strips were better than those of the ZA strip regardless of the annealing conditions. The elongations (EL) of the samples were increased as the annealing temperature was increased. For a commercial application, at least 30% of elongation is needed; hence the manufactured strips except H4D could be acceptable.

### *2.2 Corrosion Behaviors*

Figure 2 shows the weight gains from the 30 days of corrosion test. The corrosion rate increased as the heat-treatment temperature increased. In the case of the steam environment (Fig. 2(a)), the weight grains for all the manufactured strips were higher than those for the ZA strip; however, all the strips satisfied the manufacturing specification for an oxide weight grain of <22 mg/dm$^2$ in 3 days of the test.

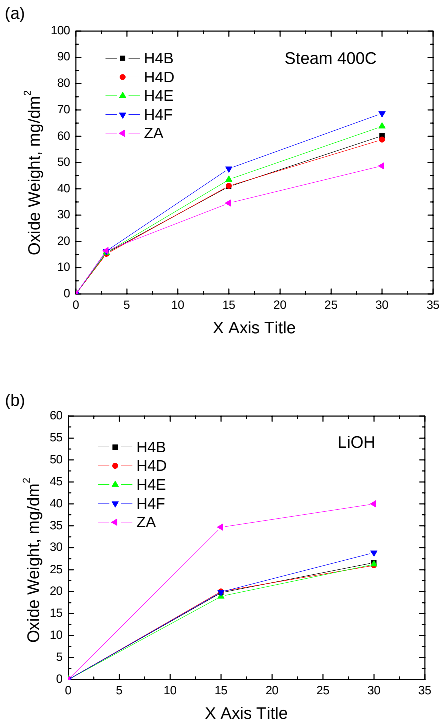


Fig. 2. Variations in weight gains of the HANA-4 strips and the ZA strip for the corrosion test in (a) a 400°C steam and (b) a LiOH environment.

On the other hand, the weight grain for the HANA-4 strip was lower than that for the ZA strip in the case of a LiOH environment as shown in Fig. 2(b). In an equilibrium Zr–Nb alloy system, $\beta_{Zr}$ phases precipitate at about 610°C. The more weight gain of the HANA-4 strip would result for the samples annealed at higher temperature over 610°C, because the $\beta_{Zr}$ phase precipitates contribute to the acceleration of the corrosion [4]. In our case, the corrosion of the H4F specimen, which underwent a high temperature of the annealing, didn't accelerated nor surpass the oxide weight gains of the commercial ZA strip. However, the formation of the second phase precipitates should be investigated for the determination of the desirable microstructures.

Due to the short duration of the corrosion tests, it is too premature to propose the current annealing conditions as a manufacturing condition for the HANA-4 strip. Nevertheless, the corrosion behaviors demonstrated in Fig. 2 suggest the possibility of a high temperature manufacturing process having a superior manufacturability.

## 3. Conclusions

The effects of the cold-rolling and annealing conditions for the HANA-4 strip were investigated. The tensile strength and corrosion properties were compatible to a commercial grade of a zirconium-based alloy. Although detailed analyses should be accompanied, it is considered that the utilized annealing conditions are acceptable for the manufacturing process of the HANA-4 strip.

## Acknowledgement

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