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Zircaloy-4 3D Printing Development Status for Nuclear Fuel Spacer Grid

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1. Introduction

A spacer grid is an important component of the nuclear fuel assembly which has a mechanical function to support and protect the fuel rod by absorbing the impact force, and it also has a thermal hydraulic function to enhance the coolant heat transfer capability. Moreover, a mid grid is directly related to fuel burn-up performance because neutron absorption rate is affected in the active fuel length as shown in Fig. 1. Thus, zirconium alloy material is generally used.

When nuclear fuel is subjected to an unwanted excessive load during shipping, handling, manufacturing and operating, the mid grid carries out crucial roles for protecting from impact and maintaining mechanical integrity. For this reason, the mid grid design requires to have superior capabilities. However, design is limited due to the current manufacturing method. To overcome this limitation, KNF is developing additive manufacturing (3D printing) technology to find possibility of manufacturing fuel assembly components. 3D printing allows to make desired shape with complex geometries using feed materials such as powder, wire, rod and so on, and using build-up technology that is different from conventional manufacturing. On the other hand, metal 3D printing with zirconium material has been rarely developed since it is easily explosive and has a high melting temperature. Moreover, producing spherical shape powder as well as controlling impurity levels to meet nuclear grade are challenging tasks.

KNF is conducting fundamental research and development for the use of zircaloy-4 (Zry-4) for 3D printing. In this paper, development status of powder production, build-up characteristics, and fundamental mechanical properties are described.

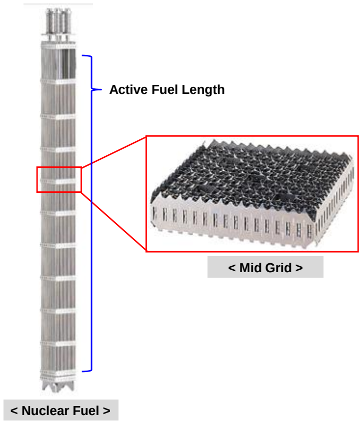
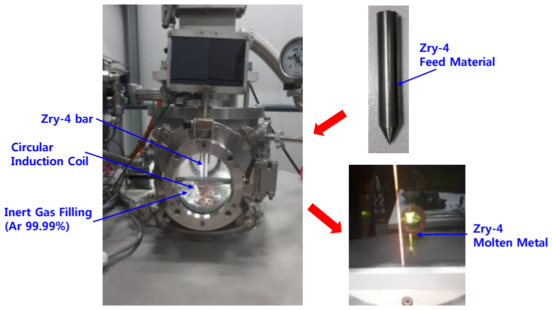


Fig. 1. Nuclear fuel and mid grid

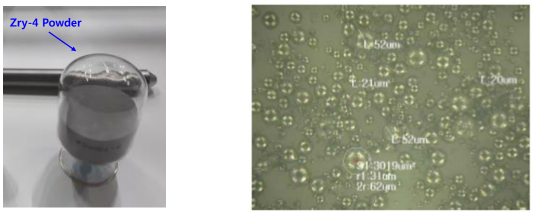
2. Zry-4 Powder

Zirconium powder is thermodynamically highly reactive and is highly likely to ignite or explode by reacting well with oxygen and hydrogen in the air. There is a very limited number of companies that produce nuclear grade zirconium 3D printing powder since zirconium powder for nuclear components should meet ASTM B352 specifications in respect of chemical composition and impurity limits. It is also required that the particle size shall be between 15~50 µm and the particle shape shall be spherical for powder bed fusion (PBF) production method [1]. KNF explored to produce Zry-4 powder with electrode induction-melt inert gas atomization (EIGA) as shown in Fig. 2(a).

As a result of inspection for the purpose of 3D printing powder, most of the evaluations of powder properties, chemical composition and optical micro scope data were satisfied as shown in Fig 2(b), (c), and Table I. But hydrogen and oxygen contents need to be examined and powder size needs to be reclassified with a strainer to have less than 50 µm at a rate of 90%.



(a) EIGA process



(b) Zry-4 powder (c) Optical microscope data

Fig. 2. EIGA process and Zry-4 powder

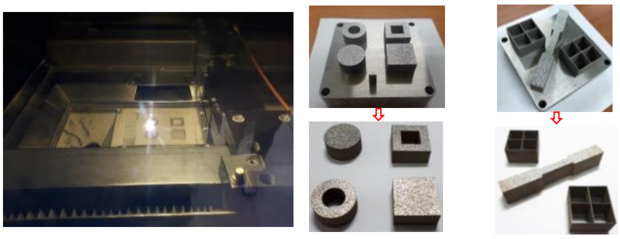
Table I: Chemical composition

Elements	Unit	Result	Standard
Zr	%	98.22	96-99
Sn	%	1.22	1.2~1.7
Fe	%	0.23	0.18~0.24
Cr	%	0.12	0.07~0.013
Nb	%	0.09	-
Mo	%	0.11	-

3. Manufacturability

Zirconium is a highly reactive metal with hydrogen and oxygen in molten state and pyrophoric in powdered state. And it has a high temperature melting point at about 1850°C. This requires not only special inert atmosphere or high vacuum working condition but also explosion proof equipment.

Figure 3 shows PBF process and 3D printed Zry-4 specimens in simple shapes. The result demonstrates that PBF manufacturing is to be capable of building-up zirconium through 3D printing.



(a) PBF process (b) Zry-4 specimens

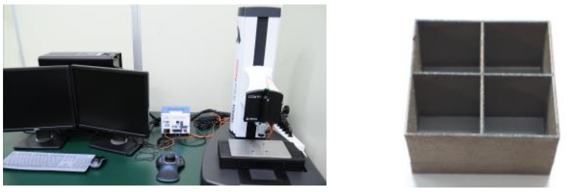
Fig. 3 PBF process and Zry-4 specimen

4. Fundamental mechanical tests

4.1 Surface Roughness

Surface roughness is related to the corrosion, fatigue, and pressure drop characteristics of the nuclear fuel. The Ra of surface roughness is regulated to 0.8 μm or less because the mechanical properties of the nuclear fuel might be deteriorated when the surface roughness is larger than that of Ra.

Surface roughness of 3D printed 2x2 grid specimen was measured using 3D surface profilometer as shown in Fig. 3(a). Figure 3(b) shows a specimen that did not apply any post-processing work for improving surface roughness or mechanical performance. From the measurement results, overall Ra of the Zry-4 2x2 grid (as-built) shows less than about 25 μm (Figure 3(c)).



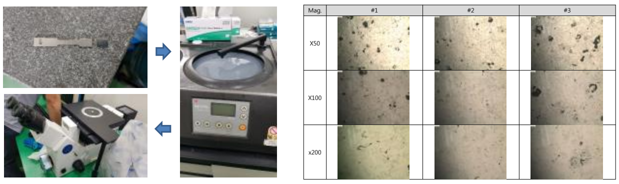
(a) 3D surface profilometer (b) Zry-4 2x2 grid (as-built)

(c) Max. measurment case

Fig. 3 Surface roughness of Zry-4 specimen

4.2 Metallographic Examination

In order to understand metallization status of 3D printed specimen via PBF technique and Zry-4 powder, simple morphology analysis was examined priorly through optical microscope as shown in Fig. 4(a). 3D printed specimen was mechanically polished but hot isostatic press (HIP) to remove pores was not considered. Figure 4(b) shows that specimen has a lot of pores and the sizes are various.

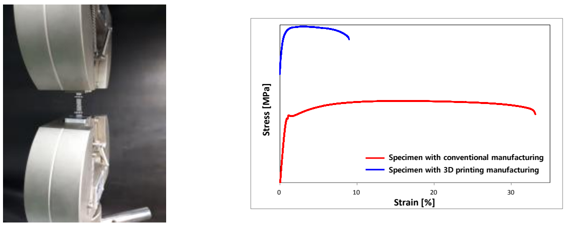


(a) Morphology examination (b) Results of surface state

Fig. 4 Morphology examination of Zry-4 specimen

4.3 Tensile Property

Tensile specimen was manufactured based on ASTM E8. The specimen was applied with surface polishing except HIP. Tensile test was performed at room temperature. And, strain was measured with video extensometer. Figure 5 shows tensile test and its results. From the comparison of the tensile test results, ultimate strength of 3D printed specimen is over 1.5 times greater than that of conventional manufactured specimen. On the other hand, strain of 3D printed specimen is about one-third smaller than that of conventional manufactured specimen.



(a) Tensile test (room temp.) (b) Comparison of the results

Fig. 5 Tensile properites

5. Conclusions

Based on the fundamental research and development that have been done so far, it is hard to draw specific features. KNF continues to manufacture test specimens and grids with Zry-4 3D printing and perform fundamental mechanical tests to achieve reliable data. The further study plan according to the variables is as follows;

- Metallographic examination
  . Post-processing work; HIP, dry electro-polishing
- Fundamental mechanical test.
  . Tensile, fatigue, impact, creep, irradiation
- Grid assembly test
  . Dynamic crush, load-deflection

REFERENCES

[1] “Additive Manufacturing Standards Structure.” ASTM website, https://www.astm.org/COMMIT/F42 ISOASTM_AdditiveManuStandardsStructure.pdf.