Lateral Crush Strength of Additively Manufactured Zirconium Alloy 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.

A mid grid among spacer grids is fabricated of zirconium alloy and it takes up most of the spacer grids in the assembly as shown in Fig. 1. Zirconium material is usually used in the active fuel length since neutron absorption rate is affected by the material.

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 process. To overcome this limitation, KNF has been developing additive manufacturing (3D printing) technology to find possibility of manufacturing fuel assembly components.

KNF has conducted fundamental research with zirconium alloy 3D printed specimens[1] and been developing spacer grids. KNF carried out dynamic crush tests of the small size (5x5) conventional spacer grid and 3D printed prototype grid to understand variations of the impact force by removing structural discontinuities. In this paper, the spacer grid manufactured by 3D printing method is introduced and the results of crush strength with two specimens are compared.

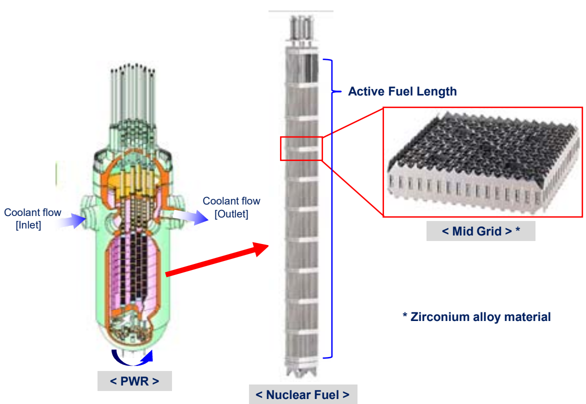
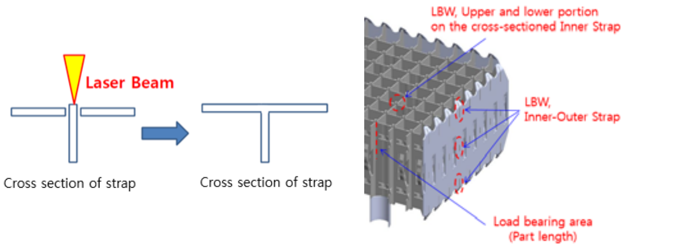


Fig. 1. Nuclear fuel and zirconium spacer grid

2. Grid Specimens

2.1 Conventional Spacer Grid

The current manufacturing method of the mid grid is a fabricated process that uses inner and outer strap with having spring, dimple, and slot made of sheet metal work. After fixing them as assembled state in a weld jig, each part is connected by laser beam welding (LBW) where it is cross-joint areas on the upper and lower portion of the strap, inner/outer strap joint parts, and the sleeve joint parts as shown in Fig. 2. The welding strength is strong but the constrained area is locally small.

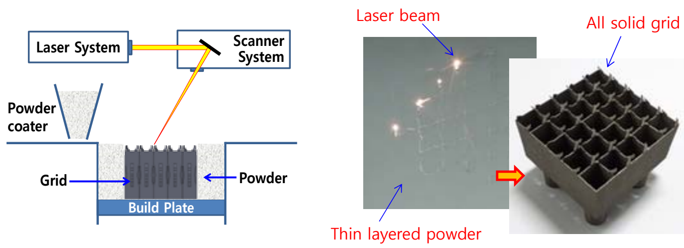


(a) LBW process concept (b) Conventional spacer grid

Fig. 2. Grid assembly through conventional manufacturing

2.2 3D printed Spacer Grid

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. Applying 3D printed manufacturing method to spacer grid can remove discontinuities such as windows behind spring/dimples and slots which are unavoidable when stamping process is used. If load-bearing area increases, resisting capability of crush energy could be improved. Fig. 3 shows concept of 3D printing manufacturing with powder bed fusion (PBF)[2] and prototype of 3D printed grid.



(a) PBF process concept (b) 3D printed grid

Fig. 3. Prototyped grid through 3D printing method

3. Lateral Crush Strength

3.1 Analytical Evaluation of Crush Strength

In order to understand variations of the crush strength by removing structural discontinuities, analytical evaluation was estimated. Conventional spacer grid and all solid grid designs were compared through evaluation. Euler column buckling formula[3] was used, as in equation (1). The input data of the dynamic impact strength for reference was used similarly shaped impact test results.

$$P_{cr} = \frac{\pi^2 EI}{(Kl)^2} = \frac{\pi^2 E}{\left(k\frac{l}{r}\right)^2} \qquad (1)$$

where, P_{cr} = Euler buckling load
k = fixity correction factor
I = cross-sectional moment of inertia
l = cell pitch inside a grid cell
r = radius of gyration
E = modulus of elasticity

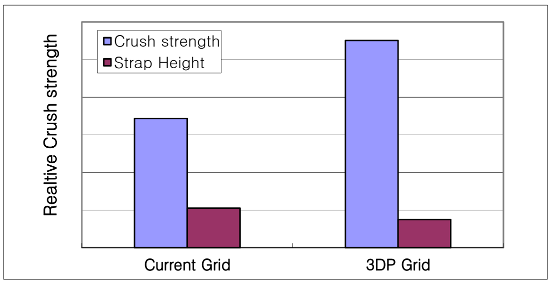


Fig. 4. Comparison of analytical evaluation for the dynamic crush strength

Table I: Comparison of the load bearing length

Items	Current grid	3D printed grid
Rel. Strap height	1.40	1.0
Rel. Load bearing length	1.65	1.0

From the analytical evaluation, it indicates that the crush strength varies by up to about 160% (Fig. 4, Table I). It means load-bearing area dominates a crucial role for resisting crush energy.

3.2 Pendulum Dynamic Crush Test

The test equipment for the dynamic crush strength consist of the hammer, load cell and high temperature furnace. The weight of the hammer is equivalent to the weight of the fuel rods within one span supported by the spacer grid. Short fuel rod cladding tubes are inserted in each cell of the test grid. The temperature for the dynamic impact test is chosen considering reactor condition. In this test, two 5x5 grid specimens were performed. Figure 5 and 6 show the schematic of the dynamic crush test equipment and grid failure modes. Both specimens have similar failure modes that show slightly rotated shape at the corner of the outside.

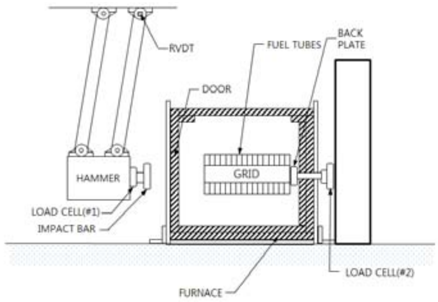
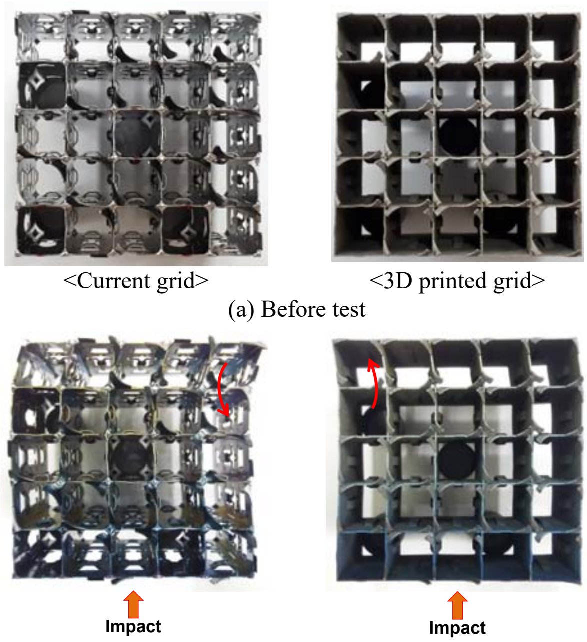


Fig. 5. Schematic of the dynamic crush test equipment



<Current grid> <3D printed grid>
(a) Before test

<Current grid> <3D printed grid>
(b) After test

Fig. 6. Grid failure modes from dynamic crush test

The dynamic crush strength in each specimen was determined at the maximum impact force before buckling which was mainly occurred in corner cell. And then the impact forces show reduced behavior after the buckling of the spacer grid as shown in Fig. 7.

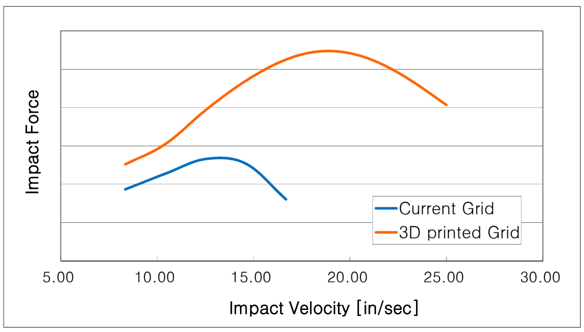


Fig. 7. Comparison of the dynamic crush test result graph

Table II shows the dynamic crush test results which are converted to relative values. It indicates that the crush strength varies by up to about 206% and the stiffness varies by about 137% at the maximum impact force. Although detail designs are partially different with each other, 3D printed grid is more conservative since the strap height is about 0.7 times smaller than the current grid. From the test, it can be concluded that load-bearing area actually dominates crush strength. The 3D printed grid can be superior compared with the current grid in terms of seismic integrity. Because the impact strength, stiffness and seismic factor of the dynamic crush test data are main inputs regarding fuel seismic performance calculation of the nuclear fuel.

Table II: Comparison of the dynamic crush test data

Items	Current grid	3D printed grid
Rel. Crush strength	0.49	1.0
Rel. Stiffness	0.73	1.0
Rel. Seismic Factor	0.57	1.0

4. Conclusions

KNF performed the dynamic crush tests. One specimen is a current grid made by conventional manufacturing process. And the other is a prototyped all solid grid made by 3D printing method. From the study, it can be clearly seen that the 3D printed grid has greater crush strength than conventional spacer grid. Thus, it is concluded that the 3D printing method could be helpful to improve dynamic impact characteristics of the spacer grid and seismic performance of the fuel assembly.

ACKNOWLEDGEMENTS

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