[MMP-05]

A Study on the Mechanical property of 3D Printing Composites in Cryogenic Environment

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I. Introduction

- ✓ The development of 3D printing technology enabled product printing using composites that include polymer-based external structures and reinforcements such as carbon, glass fibers and kevlar.
- ✓ The fuel tanks used in the aerospace industry are exposed to extreme conditions, such as room temperature and cryogenic temperature
- ✓ The cryogenics components include tanks and supports that store cryogenic fluids such as liquid nitrogen and hydrogen.
- ✓ These components require sufficient mechanical rigidity in cryogenic environments with low thermal conductivity and lightening.
- ✓ However, research on mechanical properties of 3D printing composite in cryogenic environments must be preceded because 3d printing composites are not verified properties in cryogenic.
- ✓ In this paper, we selected an FDM method 3D printer capable of printing composite materials and printed the specimen, and experimentally evaluated by constructing a test device capable of tensile strength testing in a room temperature and 77 K.

II. Production Process and Information of Specimens

▪ Applied composites material

- ✓ The 3D printing used in this study used the 'Fused Deposition Modeling' (FDM) method.
- ✓ Materials used for 3D printing are divided into main structural materials and reinforcement.
- ✓ The main structural materials are thermoplastic polymers that form all or all external structures of the objects to be printed.
- ✓ The reinforcement materials are tough and can transfer fibers to nozzles are used and the content of the reinforcement can be adjusted compared to the entire output structure.

Fig. 1. Markforged Ltd. Onyx and other reinforcement

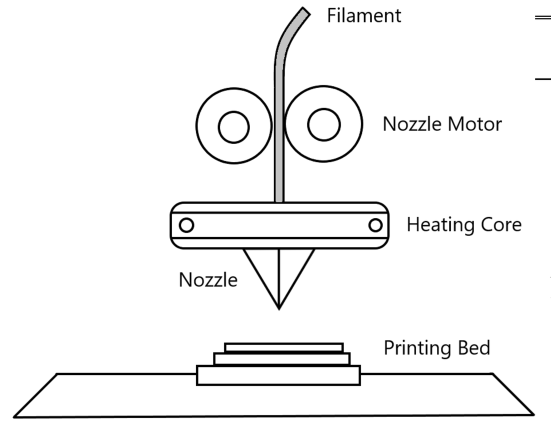

Fig. 2. FDM 3D printing method

Table 1. Specifications of 3D printer

Parameter	Value
Layer stack height (mm)	0.1
Polymer nozzle diameter (mm)	0.4
Reinforcement nozzle diameter (mm)	0.2
Printing volume capacity (mm)	320 x 132 x 154

- ✓ In this study, we used Onyx made by Markforged Ltd., which increased mechanical rigidity by adding carbon powder to nylon as the main material.
- ✓ Carbon fiber, Kevlar and glass fiber were also used as reinforcements.

▪ Specimen 3D printing for tensile test

- ✓ For tensile strength testing, each material was combined to produce a test specimen.
- ✓ The test specimen production design is based on the coupon form of the ASTM D3039 specification.

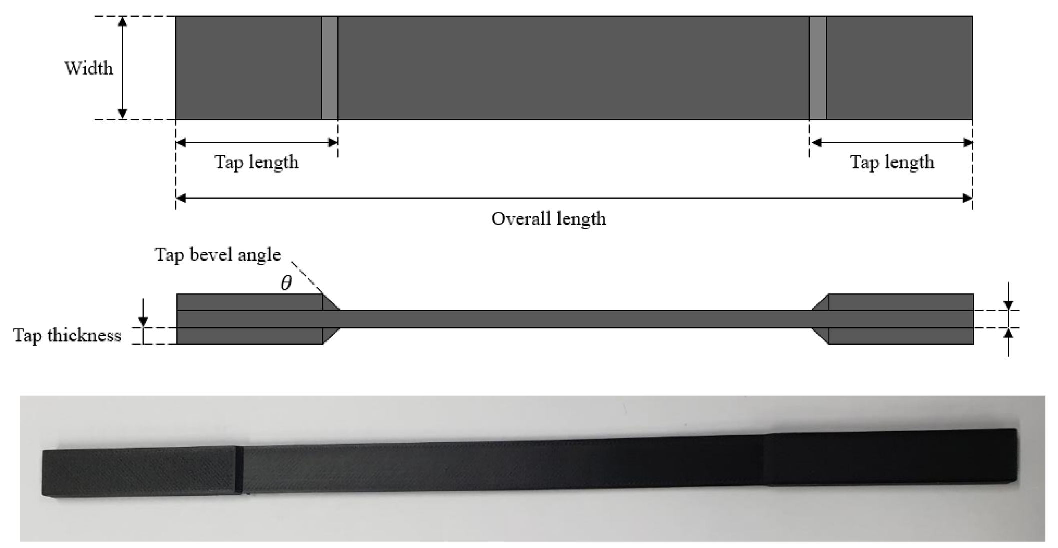

Fig. 3. Design of test specimen

Table 3. Specifications of specimen

Parameter	Value
Test specimen total size (mm)	178 x 12.5 x 1
Test specimen gauge length (mm)	60
Internal infill form	Solid fill
Test specimen cross sectional area (mm²)	4
General specimen material	100% Onyx
Configure reinforcement specimens	84%(vol.)Onyx 16% reinforcement
Applied reinforcements	Carbon fiber Glass fiber Kevlar

- ✓ Test coupons are divided into jig fixed tab and measuring part(gauging spot).
- ✓ The orientation of the fiber output of the test specimen was designed parallel to the direction of the tensile test axis (0 degrees).

III. Configure of test device

▪ Configures the tensile test device

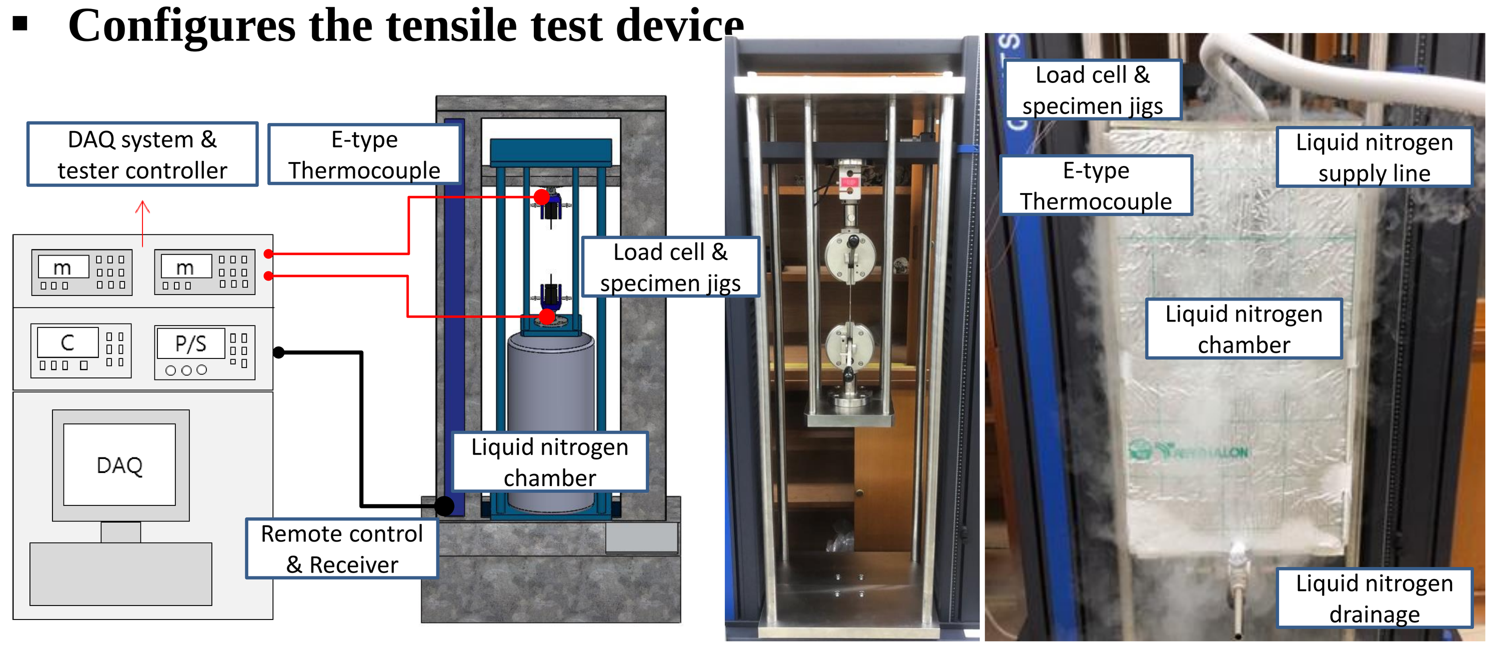

Fig. 4. Schematic diagram of the test device and its actual configuration

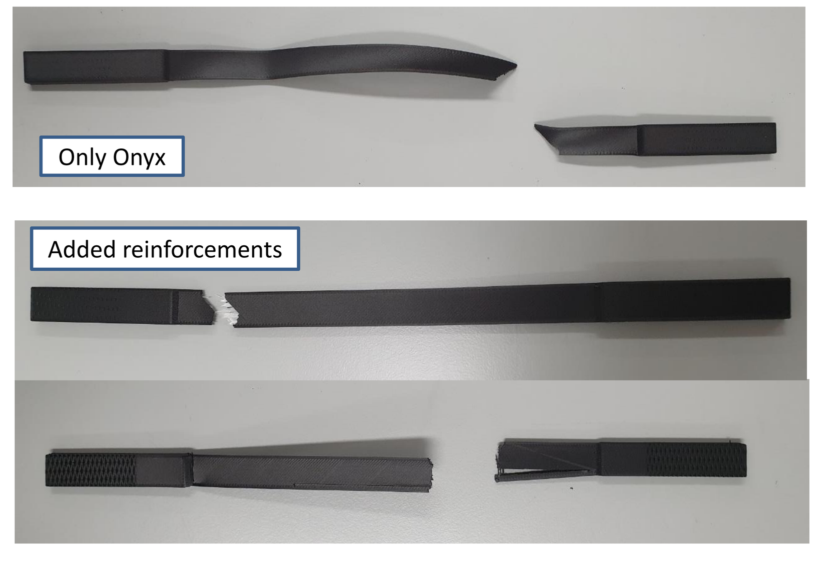

Fig. 5. Specimens of tensile test

Table 4. Tensile test conditions

Parameter	Value
Number of Tests	2 (each case)
Test temperature (K)	Room : 301 Cryogenic : 77 (in LN_2)
Maximum load (N)	10,000
Tensile velocity (mm/s)	1
Maximum displacement (mm)	200
Thermocouple location	Upper & lower jig body

- ✓ The test device was applied with tensile testing machines, including upper and lower jigs for fixing the specimen.
- ✓ E-type thermocouples on upper and lower jigs to determine temperature convergence at room temperature and cryogenic was monitored by attaching
- ✓ LN2 chamber that can hold specimens and jigs were manufactured for the cryogenic environment so that they could converge at 77K.
- ✓ The tensile test collected data by measuring the stress generated based on the displacement of 1 mm per second.
- ✓ The ultimate tensile stress and maximum displacement were measured to compare how much variation there was compared to room temperature.

IV. Test results and analysis

▪ Tensile test results

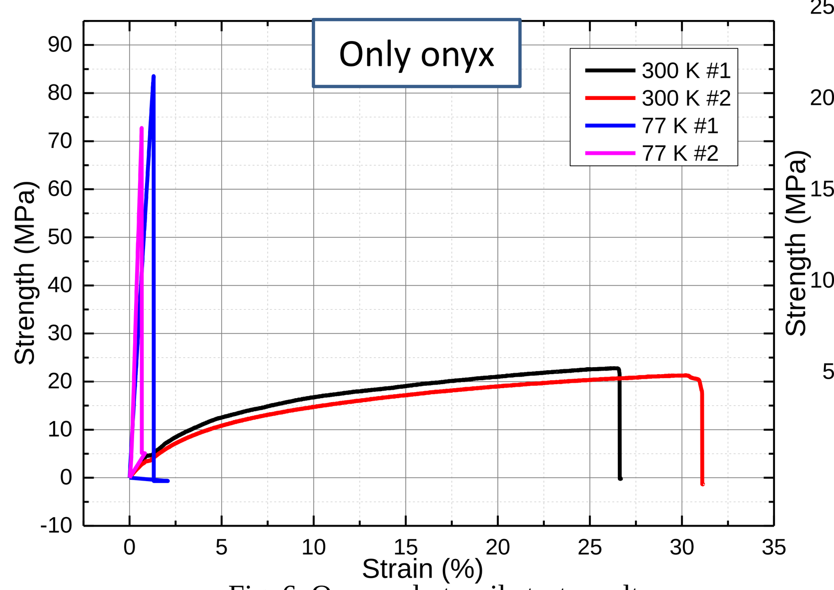

Fig. 6. Onyx only tensile test results

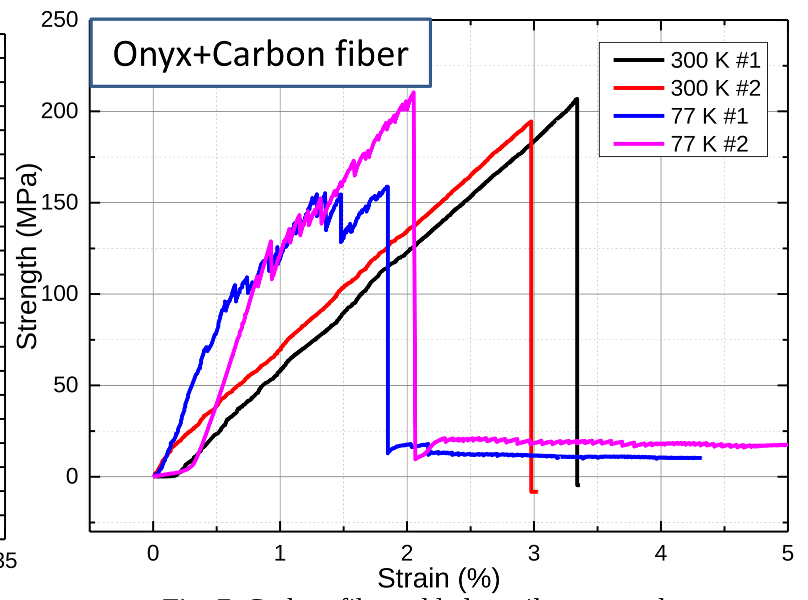

Fig. 7. Carbon fiber added tensile test results

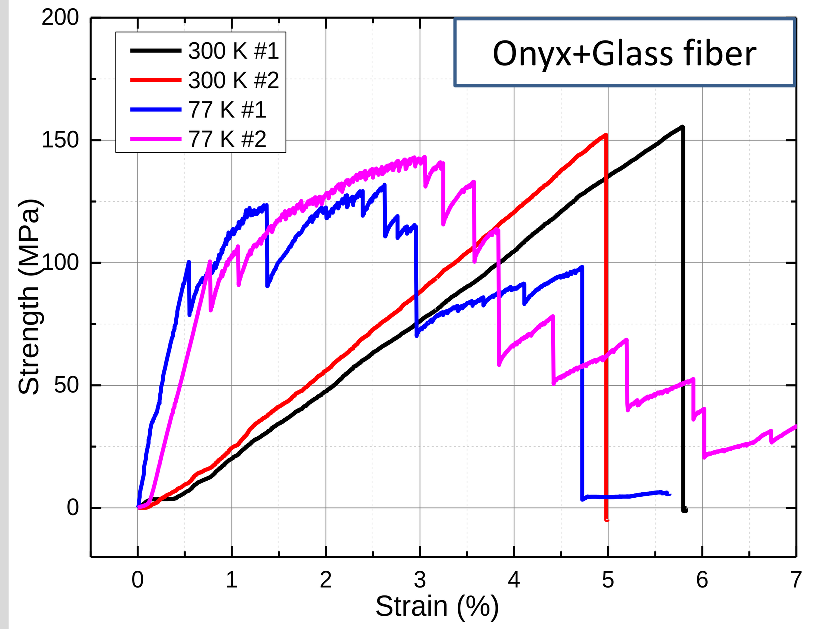

Fig. 8. Glass fiber added results tensile test results

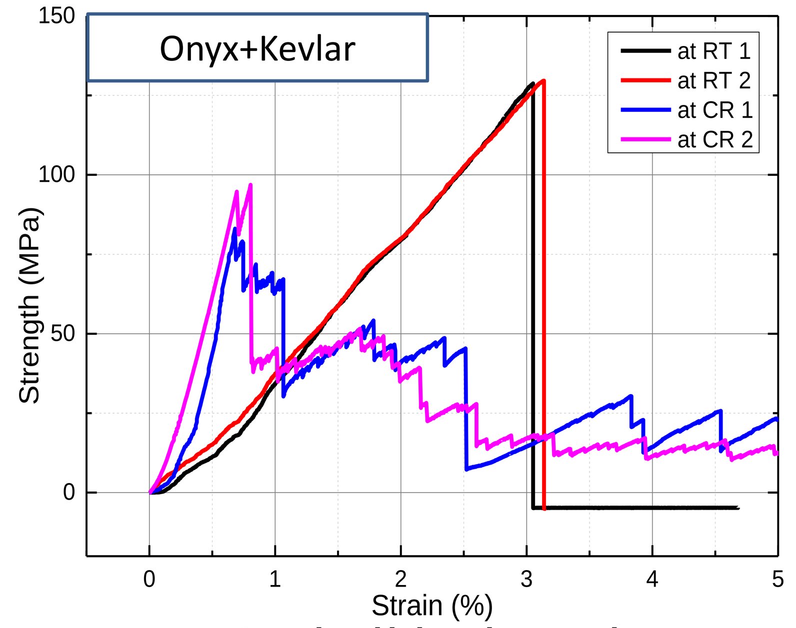

Fig. 9. Kevlar added tensile test results

- ✓ According to the comparison of Onyx, the main structure, the strain was around 30% at room temperature, but the breaking strength was around 20 MPa.
- ✓ At cryogenic temperatures, the strain was 1% and the ultimate tensile stress was 80 MPa, which increased brittleness and strength..
- ✓ Adding reinforcement case, brittleness became increased at cryogenic temperatures compared to room temperature, but the ultimate tensile stress decreased by 10-32% depending on the type of reinforcement.
- ✓ The force loaded at the ultimate tensile stress tended to decrease stepwise without being relieved all at once.

Table 6. Onyx test results

Parameter		Ultimate tensile stress (MPa)	Max strain (%)
Room	#1	27.8	27.1
	#2	29.1	31.8
Cryogenic	1 st	84.5	1.9
	2 nd	73.2	1.3
Avg. ratio of change		277.2%	5.4%

Table 6. Carbon fiber added results

Parameter		Ultimate tensile stress (MPa)	Max strain (%)
Room	1 st	214.1	3.4
	2 nd	200.3	3.0
Cryogenic	1 st	161.8	1.8
	2 nd	214.7	2.1
Avg. ratio of change		90.9%	60.9%

Table 6. Glass fiber added results

Parameter		Ultimate tensile stress (MPa)	Max strain (%)
Room	1 st	165.2	5.8
	2 nd	160.9	5.0
Cryogenic	1 st	135.3	3.0
	2 nd	147.6	3.0
Avg. ratio of change		86.8%	55.6%

Table 6. Kevlar added results

Parameter		Ultimate tensile stress (MPa)	Max strain (%)
Room	1 st	133.5	3.0
	2 nd	134.6	3.2
Cryogenic	1 st	83.7	0.7
	2 nd	97.6	0.8
Avg. ratio of change		67.6%	24.2%

V. Conclusion

- ✓ As a result, both brittleness and strength of the specimen made of polymer increased at cryogenic, but the specimen with reinforcement increased brittleness but decreased in strength.
- ✓ At cryogenic temperature, the elongation of the polymer and the reinforcement is compared and the fracture begins from a lower material.
- ✓ Therefore, since the cryogenics brittleness of Onyx is stronger than that of the reinforcement, the first fracture are similar to that of Onyx
- ✓ The results will be used as basic data for structural durability evaluation of 3D printed composite materials and data accumulation of properties.
- ✓ Therefore, further studies are needed, such as applying polymers with high elongation at cryogenic temperatures or changing the distribution of reinforcement materials.

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