WP3 – PILOT PLANTS RECONFIGURATION / IMPLEMENTATION

D3.6 – Pilot-scale development, testing and optimization of additive manufacturing processes

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ABSTRACT

The main aim of the FENIX project is the development of new business models and industrial strategies for three novel supply chains in order to enable value-added product-services. Deliverable 3.6 focuses on the Pilot-scale development, testing and optimization of additive manufacturing processes. The Direct Ink Writing (DIW) machine which requirements have been formulated in 3.5 will be developed during this task and used as pilot demonstrator and the testing and optimization of a metal loaded plastic filament FDM process. The metallic material obtained from the bio-hydro chemical recovery plant will be used to formulate a metallic ink, which will be used to print metallic green parts.

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Abbreviations and Acronyms:	
AM	Additive Manufacturing
DIW	Direct Ink Writing
FDM	Fused Deposition Modelling
STL	Standard Triangle Language
AMF	Additive Manufacturing File
3MF	3D Manufacturing Format
FDM	Fused Deposition Modelling

1. INTRODUCTION

1.1. Background

This task is directly linked to task 3.5.

During this task two processes were tested, fused deposition modelling (FDM) using Metal reinforced filament and Direct ink writing (DIW) process both with the objective of recycle has much recovered materials as possible.

Has FDM is already a state-of-the-art technology, the focus of research during 3.5 was DIW.

The key aspects of the research in lab scale were:

1) *DIW consists in depositing a pseudo-plastic ink composed of a solid load of metallic particles and a binder. This paste, contained in a siring is deposited using a XYZ displacement system and the "green" part is then sintered in a hoven, during this process the binder is burned, and the metallic particles sold together forming a solid metallic part.*

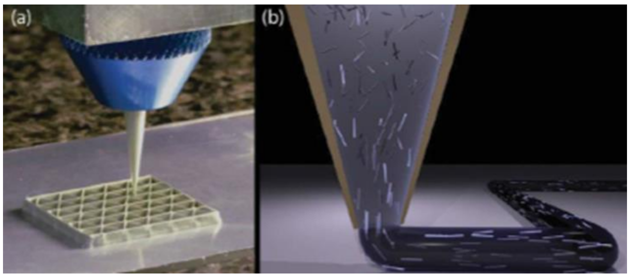


Figure 1. Principle of solid loaded DIW

2) *DIW have several advantages compared to FFF, the main been that it requires a very little quantity of material, and all the material inside the siring can be used (except the volume inside the needle) it is a very efficient process, useful when only small amounts of material are available like in this case.*

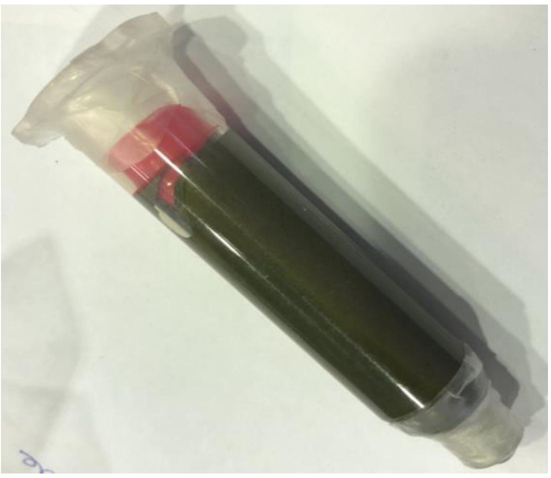


Figure 2. 10cc syringe with DIW Ink

3) *The first tests were done with commercial DIW equipment (BIO X 3D BIOPRINTER, Cellink), in which some printing parameters cannot reach a suitable value.*

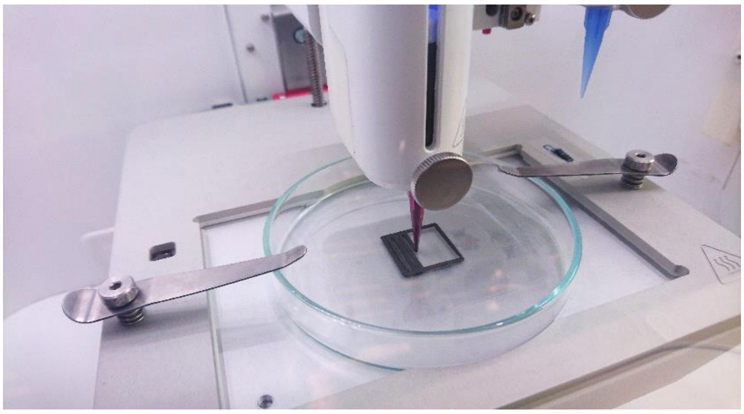


Figure 3. BIO X 3D BIOPRINTER, printing low content solid loaded ink

4) *Therefore, there is a need for the development of a beyond the state-of-the-art printer capable of printing with higher pressures which main parts are the following:*

Equipment main parts

1. Axis.
2. Printer head (Possibility to include a dual extrusion system).
3. Construction platform.
4. Auxiliary systems.

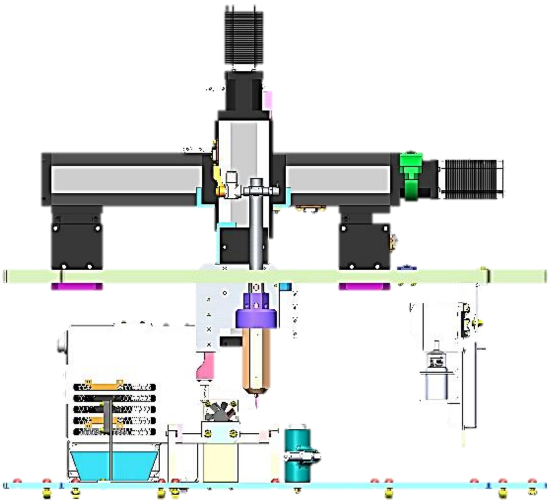


Figure 4. Conceptual design of the equipment parts

1. Axis
   - 3 Axis.
   - Marble shell.
   - Stepper motors. Resolution of 25 microns.

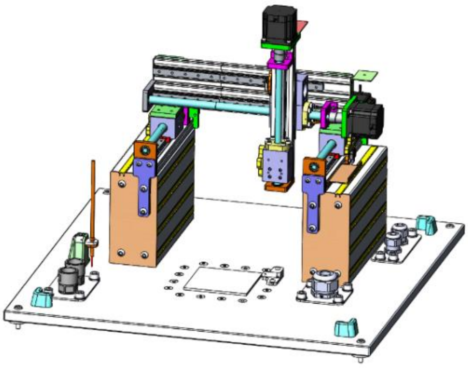


Figure 5. Concept design of the structure and the axis

2. Printer Head
   - The ink material is located in a syringe.
   - The extrusion is volumetric with a force up to 1600N
   - Possibility to include an additional extruder.
   - Auto levelling sensor for the Z offset

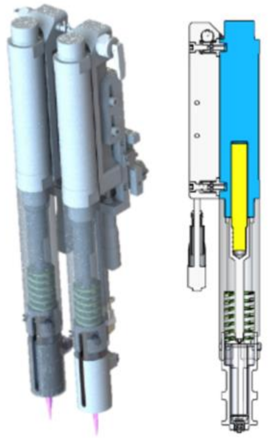


Figure 6. Concept design of the printer head

3. Construction Platform
   - Interchangeable glass.
   - Small fans used to increase the material drying if required.
   - Temperature and humidity sensors.

4. Auxiliary Systems
   - Temperature and humidity control system.
   - Insulating cover

1.2. Relation with other WPs

Within the FENIX project additive manufacturing is the main method of valorisation of the recovered WEEEs material therefore this task has a relation with all the WPs, as it closes the loop of circular economy.

Anyway, a special mention should be made for:

- WP2 which will realise the LCA of the pilot plants
- WP6 The Use cases that are going to be manufactured by the pilot plants

1.3. Organization of the work

The work within task 3.6 will therefore consist in 3 main parts:

1) Design and development of the required DIW printer
2) Printing parameters optimization of the FDM additive manufacturing process

3) Printing parameters optimization of the DIW additive manufacturing process

2. DESIGN AND DEVELOPEMENT OF THE REQUIRED DIW PRINTER

This task follows the work realized in T3.5 FCIM oversees the design and fabrication of the DIW equipment.

2.1. Specification and Concept design

Figure 7. render of the final design

Lab-scale testing of Additive Manufacturing Processes using the Direct Ink Writing (DIW) technology. To do that, materials from the recovery process are used (iron and copper) and printing parameters of Additive Manufacturing processes are determined in order to build-up functional 3D parts.

The initial tests were carried out to develop an ink suitable for a Direct Ink Writing (DIW) process. Two different powders have been received from the consortium: Iron based powder and Copper/Tin powder.

These first tests are done with commercial DIW equipment (BIO X 3D BIOPRINTER, Cellink), in which some printing parameters cannot reach a suitable value. Consequently, the ink cannot be loaded with more than a 35% of solid content in volume (for the iron-based ink) due to mechanical limitations. The pressure used to print the ink was 170Kpa (1,7Bars) and the maximum possible effective pressure for this printer is 200Kpa (2 Bars), even if the machine datasheet announce a pressure up to 700kpa (7 bars) this is a theoretical mechanical limitation of the components not the real use values, which are much lower.

The pressure needed to print a pseudo plastic ink is due to 2 factors, the dynamic viscosity of the binder and the behaviour of the solid content. In this case we are going to reduce the amount of binder so it will be less of an issue. But on the other hand we are going to increase the solid content which will be the cause of the increase of the pressure. The question being What will be the pressure needed to print a higher solid content?

The mechanical behaviour of a powder evolves following the following general rule: the powder can be considered as a «fluid» until reaching a certain density called «packing density» then it should be considered as a solid.

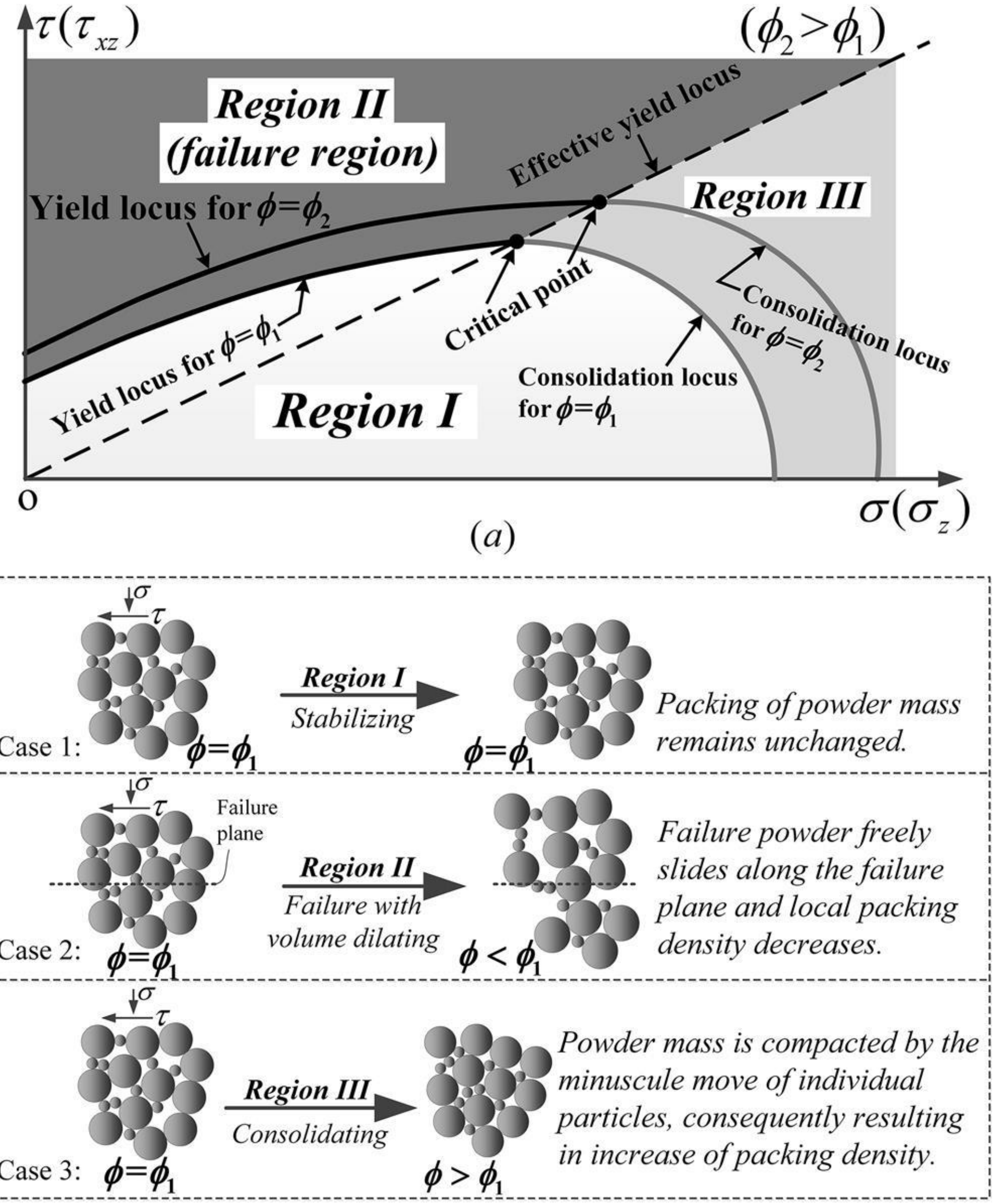


Figure 8. New strategies for powder compaction in powder-based rapid prototyping techniques A. Buddinga*, T.H.J Vanekera (2013)

This vison fits very well whit Heckel's equation in rheology (1961) which is the following:

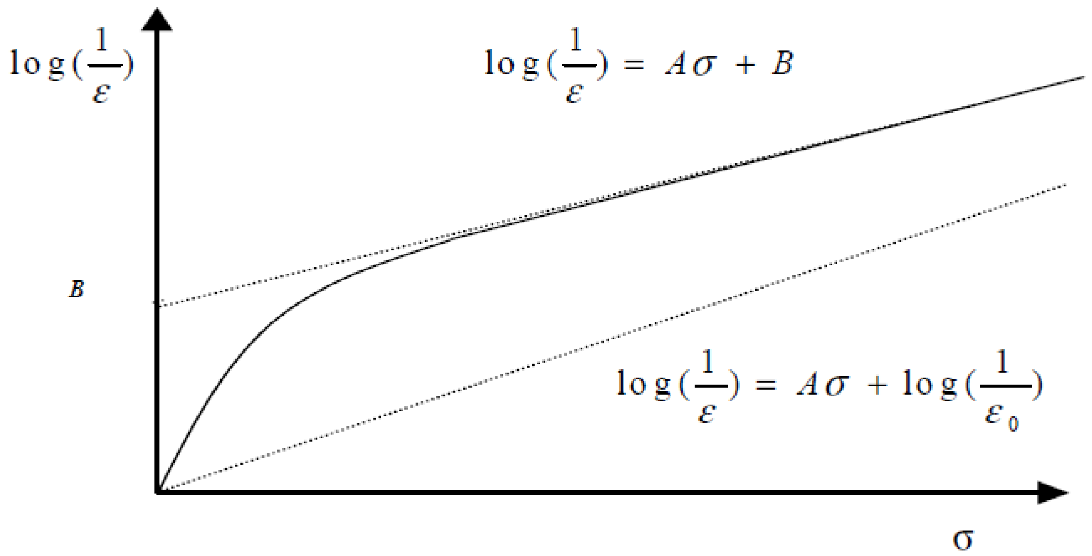


Figure 9. Heckel's equation in rheology (1961)

Where ε is the relative deformation, σ the pressure applied, A the constant of plasticity of the material and B is a constant defined by the geometry and bonding condition of the particles.

We don't have all the data to solve this equation and fully model our system, but we can use it to make assumptions.

1st assumption: Gauss demonstrated that the maximum average density of a space occupied by spheres is $\frac{\pi}{3\sqrt{2}} \approx 0{,}74048$ so for a monomodal perfect powder this would be our packing density.

2nd assumption: Increase of density is equivalent to the relative deformation of Heckel's equation.

3rd assumption: The B component of the equation can be neglected since we are modelling perfect rigid spheres and that the binder acts as lubricant.

Then the Pressure required to print the maximum possible solid load content (74%) should be around 14 Bars, far away from the reach of any commercial printer.

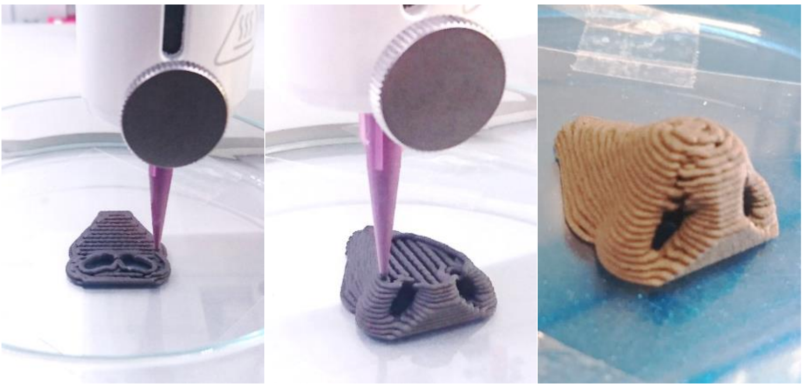


Figure 10. Nose structure printed using DIW technology with an iron based ink

The debinding process was done with a reducing atmosphere of Argon/5%H2. The results of both processes can be observed in Figure 10, Those results even if visually acceptable, have shown the necessity of developing a special purpose equipment in order to be able to print Inks with a higher solid content, thus limiting the retraction in the final sintered part and consequently increase its mechanical properties.

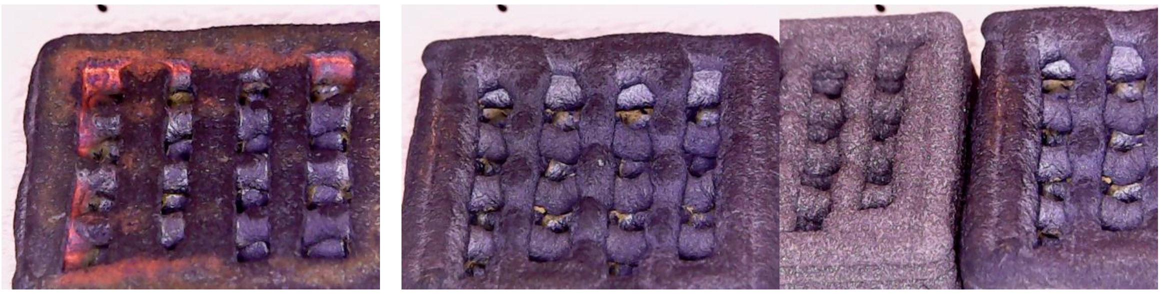


Figure 11. Result after the debinding and sintering process

In order to give to the recycled materials, the maximum added value as possible, the following objective is then to develop a Direct Ink Writing equipment for the lab scale testing, able to print all FENIX's new 3D materials. This new equipment will then be able to print inks with a higher solid contend and as well improve the control of printing chamber conditions.

Ref	Type	Max Force (N)	Weight (Kg)	ratio (N/kg)
LSA201S06-A-UECB-102	Nema 8	33,7	0,063	534
LSA281S10-A-THCA-152	Nema 11	130,7	0,13	1005
LS3518S1204-T5X5-75	Nema 14	160	0,15	1066
LSA421L18-B-UKGI-152	Nema 17	275	0,4	687
LS5918S2008-T10X6-75	Nema 23	500	0,85	588
Expected Value for 1000N	-	1000	1,72	579
CHMB32-75	Hydraulic	2814	0,74	3802

Figure 12. Comparison table between different pressure systems

Traditional Volumetric DIW systems usually use a linear motion system driven by a stepper motor, and their Max force increases linearly with their weight. As shown in Figure 12, a 1000N actuator is expected to have a weight of 1,72kg. 1600N have been chosen because it's the force required to apply a 14Bars pressure inside a 5cc syringe (The print head will be able to hold syringes of 10; 5 & 3 with only minor changes).

With a "Y Gantry" configuration for the positioning system, the Printer head is mounted on the Z axis, itself mounted on the X axis, itself mounted on a Double Y axis. Consequently, any increase of the weight of the extruder requires an increase of the dynamic capabilities of the entire positioning system increasing its price by a square factor. For this reason, a direct increase of the pressure force must be realized by another system more efficient in term of Force/Weight ratio.

A hydraulic piston has a much higher force to weight ratio, allows easily the required force, is fairly compact (Ø32 compared with a 6 bars compressed air piston) and as the hydraulic oil is incompressible it can be controlled as precisely as a direct Stepper drive solution.

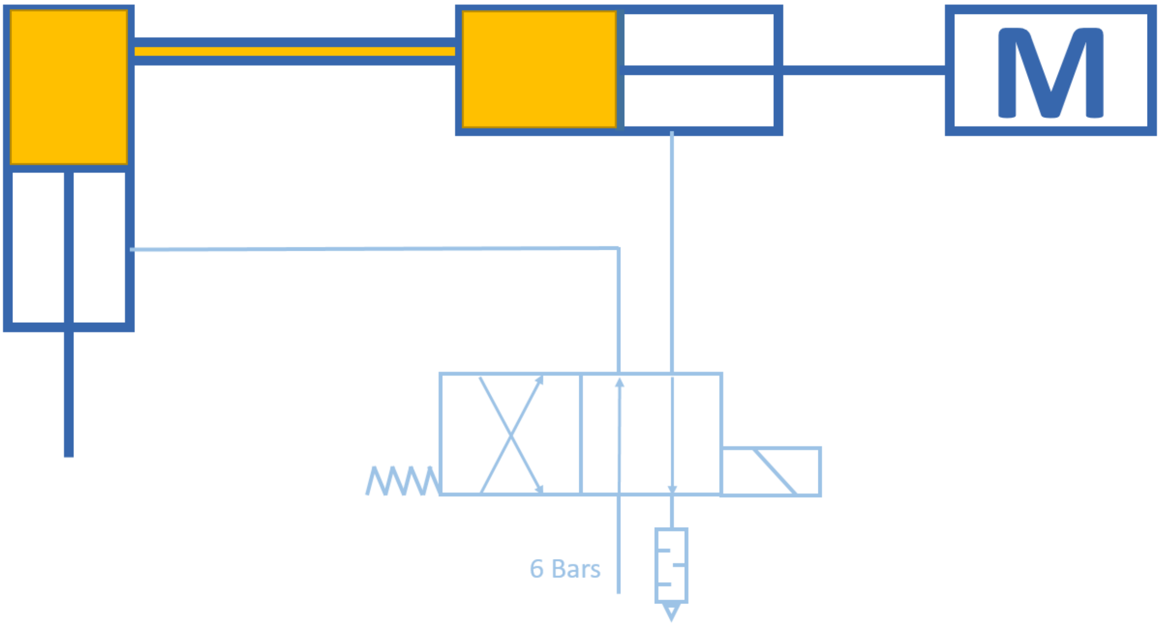


Figure 13. Final design of the pressure system

The final setup for the extruder is formed by a hydraulic piston driven by a stepper motor and assisted pneumatically.

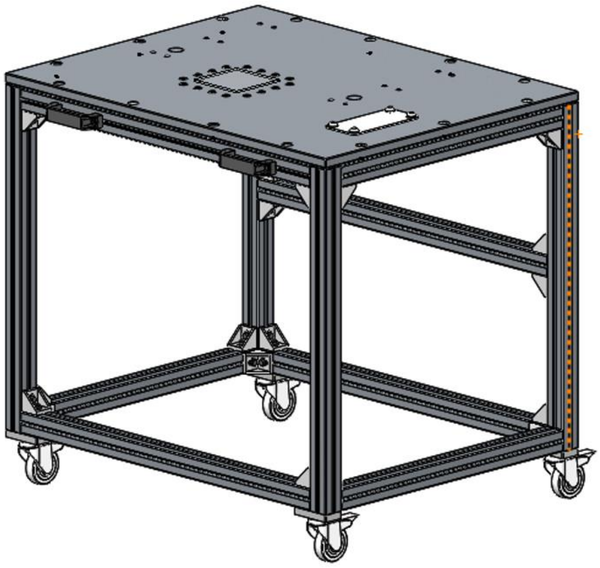
The main requirements of the equipment to be developed in task 3.6 where defined and are listed below:

- Small Printing Volume (100x100x100) mm.
- AM material is extruded by a hydraulic system.
- Temperature and humidity control of the manufacturing volume.
- Structure:
  - Commercial aluminium profiles.
  - Methacrylate casing designed to control the temperature and humidity of the manufacturing domain.
  - Easy to move.

2.2. Detail design and fabrication

Following those are the element that are already designed and mounted:

- Structure: the structure is made with commercial aluminium profiles subjected by angles. Wheels with brakes allow an easy mobility.



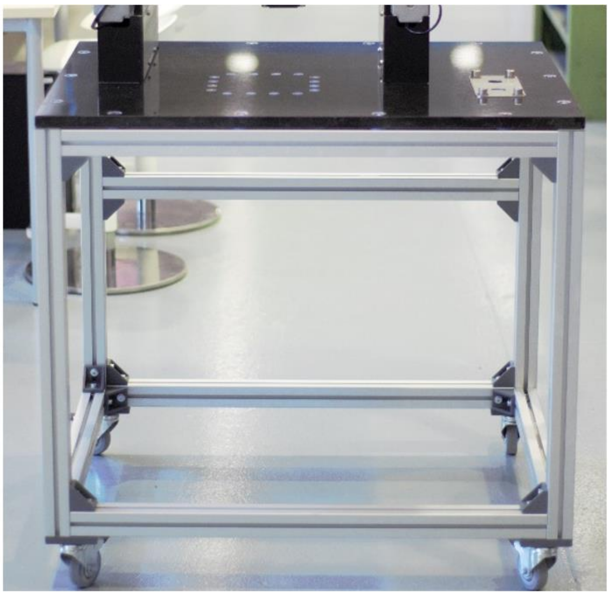


Figure 14. Detail design of the structure and real picture

- Axis: 3 axes are implemented, Y axis is mounted in a gantry setup (2 parallel and synchronized carriages), XZ Axis are orthogonal single carriage. Each axis possesses an end stop sensor which allows to the machine to find a reference point in space from which each position of the tool head are calculated (homing process). All parts are assembled and configured.

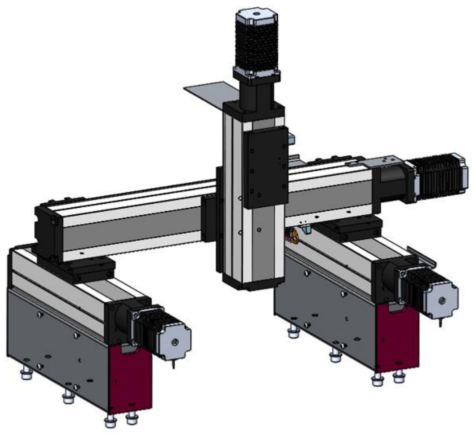
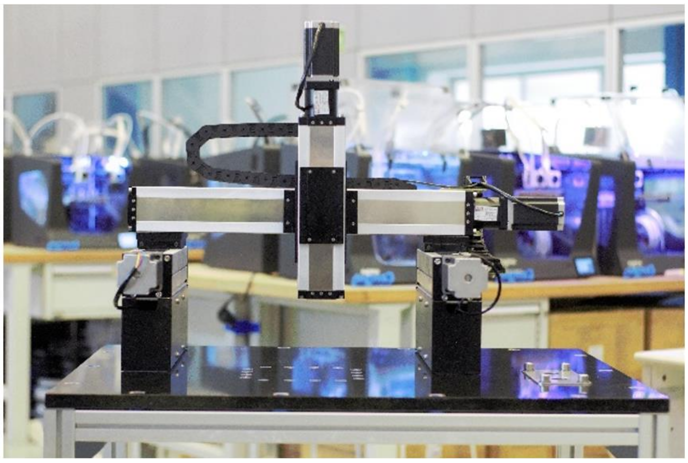



Figure 15. Detail design and the result of the axes

- Printer Head: The main parts are machined and a first assembly for design validation is done. However, the design needs some adjustments that require the redesign of some parts in order to improve the syringe assembly. This adjustment is still in course.

A probe sensor is included in the extruder head and its function is to create a 3D mapping of the extruder head with the print base doing point mapping.

In this design, the standard syringe capacity is 10cc capacity, but it is possible to change it to 3cc or 5cc capacity syringe. And, as it was previously mentioned, the extrusion is volumetric with a force up to 1635N.

This force will allow to apply a pressure of 10 Bars on the ink inside a 10cc syringe. Enough to meet the expected maximum pressure. The main limitation to the applicable pressure is the syringe which is designed to hold a 7bar pressure by itself but in this case is located in an aluminium jacket that should allow it to hold much more pressure.

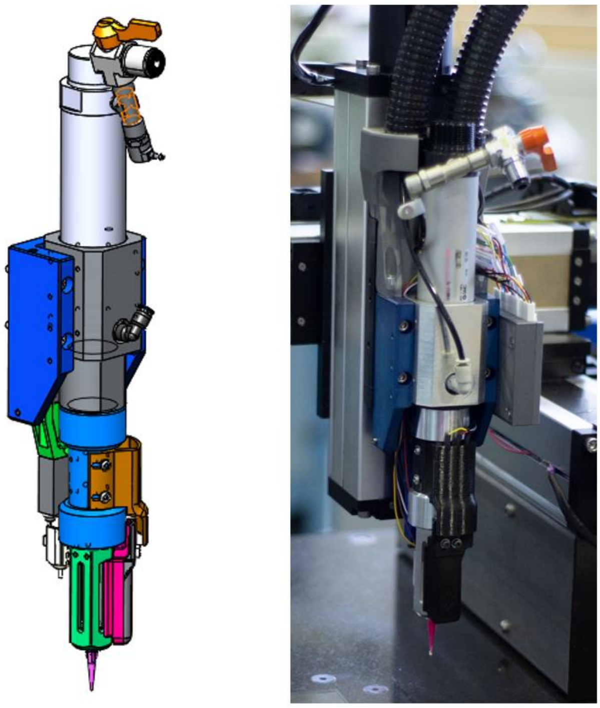


Figure 16. Detail design and the result of the Printer Head

There is also the option to include one or two extra extruders in the printer head. These extra extruders when are not being used, are at a higher level than the main extruder in order to avoid the damage of the printing when the last is in use. A system of pneumatic offsets allows to have the extruder in use always at a lower level than the ones that are not in use.

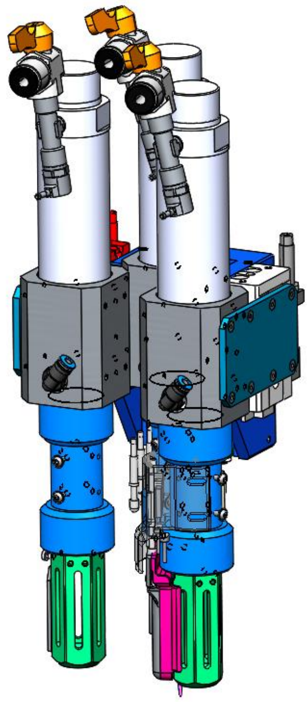


Figure 17. Printer Head with three extruders

- Construction Platform: All the parts are assembled except the temperature and humidity sensor, which will be mounted in one of the threads around the print base.

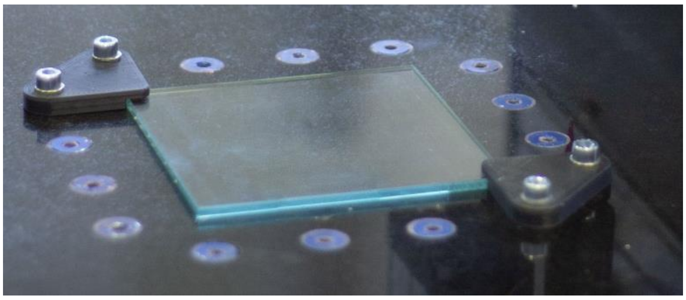


Figure 18. Result of the construction platform

- Auxiliary Systems
  - Temperature and humidity control system.
  - Insulating cover

The auxiliary systems and insulating cover are still being implemented at this date are expected to be ready in the next months.

The main part of the temperature control system is the heater. Even though it is a tested system, it must be checked with the whole assembly.

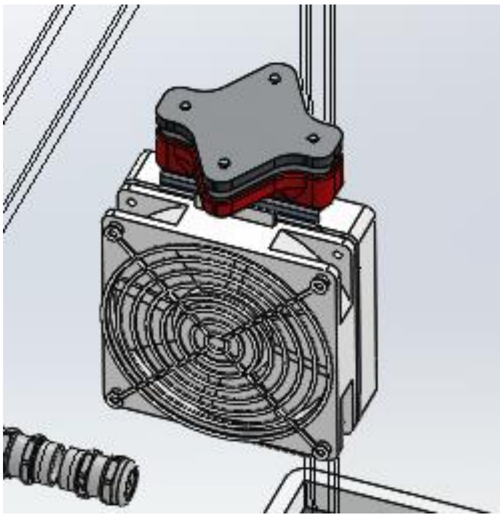


Figure 19. Heater of the temperature control system

The humidity control system is in phase of concept design. As the temperature control system, it must be checked with the whole assembly.

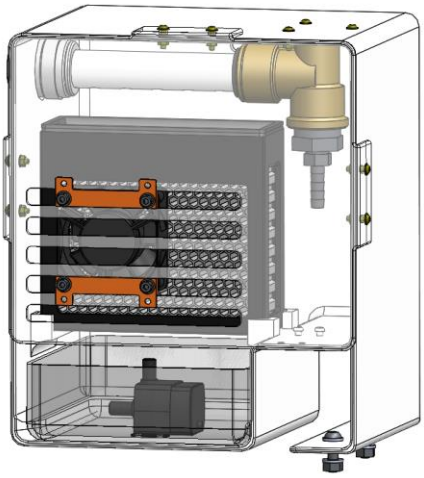


Figure 20. Concept design of the humidity control system

The humidity control system is composed of a pump, a filter, two funs, a water container and a system which let the water fall into the filter. When the water falls inside the filter, the fans create an airstream which goes directly into the cover. The remaining water falls into de container and it starts the same process.

3. PRINTING PARAMETERS OPTIMIZATION OF THE DIW PROCESS

The next step after the realization of the device is a series of tests in order to validate that it works correctly and meet the requirements exposed in task 3.5

The test of the machine is divided between 2 series:

- The preliminary test has the objective to check that the machine is able to realise a good quality deposition of a standard ink and that the machine is able to depose an ink with the components that are going to be used later in the project.
- The validation tests will be carried out only using ink loaded with recycled material and also have 2 objectives: produce a series of samples and check the influence of temperature on the ink for this reason it was divided in two sub-series, the red series without temperature control and the blue ones using a hot bed.

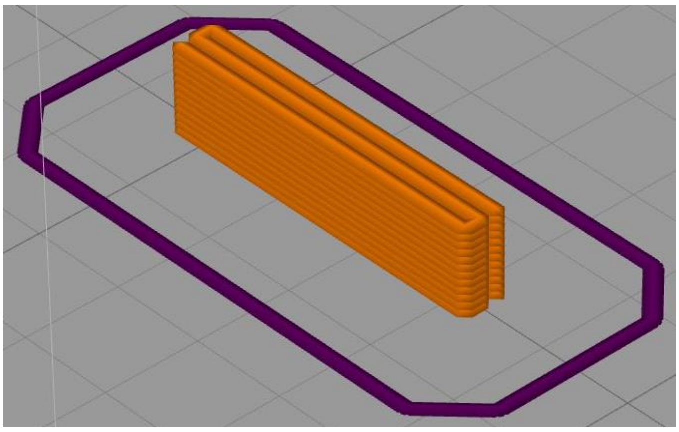


Figure 21. Path planning of the print of the sample with layers deposited in the long direction

For purposes of WP6 the same sample is printed in two different directions, short and long, in order to study the effects of the internal structure on the final part.

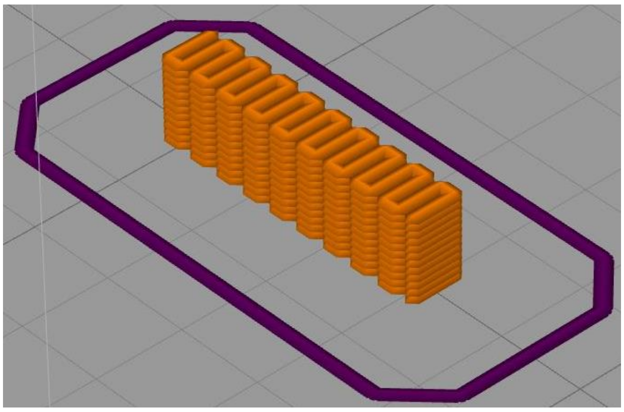


Figure 22. Path planning of the print of the sample with layers deposited in the short direction

H2020 Innovation Action - This project has received funding from the European Union's
Horizon 2020 research and innovation programme under grant agreement N. 760792

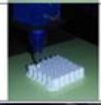
Reference			Printing Parameters				Tip parameters			Results				Post treatment		
ID	N. impr.	Material	Gcode	Layer heigh (mm)	Speed (mm/min)	Temp.º	Extruder width (mm)	Tip Ø (mm)	Tip material	complete?	Satisfactory?	Image	Observations	Type	Temp.º	Atmos.
051119R01	1	Test material Alumina	Cilinder spiral	0,3	600	25	0,5	0,41	inox	25%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R02	2	Test material Alumina	Cilinder spiral	0,3	600	25	0,5	0,41	inox	25%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R03	3	Test material Alumina	Cube-45Infill	0,3	1200	25	0,5	0,41	inox	30%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R04	4	Fe Bimodal 45% Volumen	Probeta halterio-perimeters	0,4	600	25	0,7	0,58	Poly-propylene	8%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R05	5	Fe Bimodal 45% Volumen	Cilinder spiral	0,4	600	25	0,7	0,84	Poly-propylene	1%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R06	6	Fe Bimodal 45% Volumen	Probeta halterio-perimeters	0,4	600	25	0,7	0,84	Poly-propylene	10%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R07	7	Fe Bimodal 45% Volumen	Cube-45Infill	0,4	600	25	0,7	0,84	Poly-propylene	100%	No		Once printed the construction falls down 	NS/NC	NS/NC	NS/NC
051119R08	8	Fe Bimodal 45% Volumen	Probeta halterio-perimeters	0,4	600	25	0,7	0,84	Poly-propylene	100%	Yes			NS/NC	NS/NC	NS/NC
051119R09	9	Fe Bimodal 45% Volumen	Probeta halterio-perimeters	0,4	600	25	0,7	0,84	Poly-propylene	6%	No		Tip gets blocked	NS/NC	NS/NC	NS/NC
051119R10	10	Test material Alumina	Probeta halterio-perimeters	0,4	600	25	0,7	0,84	Poly-propylene	100%	Yes			NS/NC	NS/NC	NS/NC

Figure 23. Summary of the Preliminary Tests of the DIW device

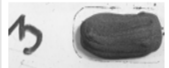
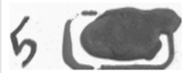
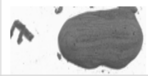
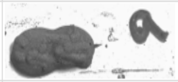
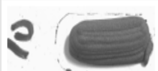
Reference			Printing Parameters						Tip parameters			Results							
ID	N. impr.	Material	Gcode	Layer heigh (mm)	Speed (mm/min)	Temp.º	Infill orientation	Flow	Extruder width (mm)	Tip Ø (mm)	Tip material	Printing time	Weight (grams)	Consume (W)	Complete?	Satisfactory?	Image	Observations	Type
041219R01	1	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	19,3	Long	–	0,86	0,47	Poly-propylene	2:30	0,51	64,4	Yes	No		Liquid and fast	
041219R02	2	Fe Bimodal 45% Volumen	04_07_Long	0,4	250	19,3	Long	–	0,86	0,47	Poly-propylene	3:20	0,8	64,4	Yes	No		Liquid	
041219R03	3	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	Material: 21,8	Long	–	0,86	0,47	Poly-propylene	2:30	2,34	64,4	Yes	No		Liquid and too much flow	
041219R04	4	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	22	Long	423	0,86	0,47	Poly-propylene	2:30	1,96	64,4	Yes	No		Syringe with air	Syringe holder heated
041219R05	5	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	19,8	Short	423 a 235	0,86	0,47	Poly-propylene	3:10	1,08	64,4	Yes	No		Liquid and syringe with air	Syringe holder heated
041219R06	6	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	19,7	Long	266 a 106	0,86	0,47	Poly-propylene	1:10	0,5	64,4	Yes	No		Liquid	Syringe holder heated
041219R07	7	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	19,7	Long	350 a 220	0,86	0,47	Poly-propylene	1:18	1,18	64,4	Yes	No		First liguid, after solid. After, it falls down	Syringe holder heated
041219R08	8	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	21	Long	220	0,86	0,47	Poly-propylene	2:18	1,12	64,4	Yes	Printable		In the beginning the Tip blocked	Aply heat while printing
041219R09	9	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	21	Long	220	0,86	0,47	Poly-propylene	2:18	0,59	64,4	Yes	No		Tip blocked	Aply heat while printing
041219R10	10	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	21,5	Long	350 a 220	0,86	0,47	Poly-propylene	3:18	1,58	64,4	Yes	Printable		Not precised	Aply heat while printing
041219R11	11	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	21	Long	246	0,86	0,47	Poly-propylene	2:20	1,36	64,4	Yes	Printable		After printing it falls down a	printing

Figure 24. Summary of the Red Case Validation test

Reference			Printing Parameters						Tip parameters			Results							
ID	N. impr.	Material	Gcode	Layer heigh (mm)	Speed (mm/min)	Temp.º	Infill orientation	Flow	Extruder width (mm)	Tip Ø (mm)	Tip material	Printing time	Weight (grams)	Consume (W)	Complete?	Satisfactory?	Image	Observations	Type
041219B01	12	Fe Bimodal 45% Volumen	Pause_04_0	0,4	350	22	Long	230	0,86	0,47	Poly-propylene	2:30	1,13	64,4	Yes	Yes		Precised	Aply heat while printing
041219B02	13	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	22	Long	215	0,86	0,47	Poly-propylene	2:30	1,15	64,4	Yes	Yes			Hot bed
041219B03	14	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24,1	Long	220	0,86	0,47	Poly-propylene	2:30	1,3	64,4	Yes	Yes			Hot bed
041219B04	15	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24,2	Long	213	0,86	0,47	Poly-propylene	2:30	1,07	64,4	Yes	Yes		Broke after	Hot bed
041219B05	16	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24,3	Long	220	0,86	0,47	Poly-propylene	2:30	1,12	64,4	Yes	Yes			Hot bed
041219B06	17	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24	Long	207	0,86	0,47	Poly-propylene	2:30	1,02	64,4	Yes	Yes			Hot bed
041219B07	18	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24,1	Long	210	0,86	0,47	Poly-propylene	2:30	1	64,4	Yes	Yes			Hot bed
041219B08	19	Fe Bimodal 45% Volumen	04_07_Long	0,4	350	24	Long	217	0,86	0,47	Poly-propylene	2:30	1,18	64,4	Yes	Yes			Hot bed
041219B09	20	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	24	Short	214	0,86	0,47	Poly-propylene	3:15	1,31	64,4	Yes	Yes			Hot bed
041219B10	21	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	24	Short	214	0,86	0,47	Poly-propylene	3:15	1,38	64,4	Yes	Yes			Hot bed
041219B11	22	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	23,8	Short	260	0,86	0,47	Poly-propylene	3:15	1,22	64,4	Yes	Yes			Hot bed
041219B12	23	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	23,5	Short	270	0,86	0,47	Poly-propylene	3:15	0,73	64,4	Yes	No		Last layer no good flow	Hot bed
041219B13	24	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	23,5	Short	293	0,86	0,47	Poly-propylene	3:15	1,1	64,4	Yes	No		Last layer no good flow	Hot bed
041219B14	25	Fe Bimodal 45% Volumen	04_07_Short	0,4	350	23,5	Short	350	0,86	0,47	Poly-propylene	3:15	0,26	64,4	Yes	No		First layer is not well attached. Syringe with recycled material	Hot bed

Figure 25. Summary of the Blue Case of the validation test

4. PRINTING PARAMETERS OPTIMIZATION OF THE FDM PROCESS

Fused Deposition Modelling (FDM) additive manufacturing process is the most widespread 3D printing processes today due to the low cost of the necessary equipment and the abundance of the feedstock materials. Although a simple method, it involves a rather large set of printing parameters that must be determined for every single material used. Extruder temperature, printing speed, nozzle diameter, retraction distance, layer height are the most critical parameters of the FDM process. Up to now, the polymers which are tailored for the FDM process, mainly thermoplastics, can be easily tuned for delivering a near perfect outcome. In fact, many material suppliers provide material configuration files which can be fine – tuned by the users.

On the other hand, the addition of inorganic fillers does change the behaviour of the composite thermoplastic during the FDM printing process. The melted material is more viscous which in turn adds more pressure during the material flow. As the percentage of the inorganic filler increases, nozzle blockage becomes the major concern. It occurs due to the agglomerations that the inorganic powder forms. The latter can happen during the filament production, as a result of weak shearing during compounding or while printing due to increased melt pressure. Another issue is the filament fragility when the filler material is more than 50 wt.% approximately. This issue can become so severe, that can render the filament unusable.

As current filament materials come in two different diameters (1.75mm/2.85mm), initial trials were conducted using two different 3D printing systems to cover both cases. RAISE3D N2 PLUS for 1.75mm variant and ULTIMAKER 3 FDM 3d printer for 2.85mm. The specific printers were chosen mainly because of the provided open source architecture (any material and any slicer software can be used). In this case open source CURA was used so as to freely determine every parameter of the printing process. During these trials filament handling and feeding to the extruder proved to be very difficult. It was not possible to feed the filament through the PTFE feeding tube with success. The filament was prone to fracture very easily with the lightest bending. The solution to this issue was the use of two different filament pre-heating systems. An 1kW common home air heater device positioned outside of the printers which was used to heat the entire filament spool and a specialized filament heater which was used to heat the filament before entering the extruder. The purpose of this heating is to overcome the "memory" effect of the polymers that surround the metal particles which have the tendency to keep the round shape of the filament spool. Heat relaxes the polymer bonds and helps using such filaments with less fractures.

After the filament fragility issue was overcome, the appropriate extruder temperature was determined. Since the filament polymer was PLA (Polylactic Acid) which is commonly heated up to 180-200°C during 3D printing processes, the tested temperature range was set between 180-230°C, with a 10°C step. Due to the higher melt viscosity it was expected that the appropriate printing temperature of the metal-filled filament should be higher than the PLA's one. Between 180 and 200°C random filament grinding was observed which resulted to decreased material supply. At 210°C and above, no filament grinding occurred.

The next step was to determine the appropriate nozzle diameter size. The tests were conducted using brass and nickel-plated nozzles (less friction and greater resistance to wear due to the abrasive materials) with diameters from 0.4 up to 0.8mm. The necessary printing parameters were kept unchanged. Only the print with the larger nozzle tip was successful. Random clogs were observed during the printing tests with nozzles with a tip diameter of 0.4mm where 0.6mm and 0.8mm nozzles offered greater reliability.

The last step was to determine the optimum printing velocity and retraction settings. Retraction is the recoil movement of the filament necessary to prevent dripping of material during movements and displacements that the extruder performs during 3D printing. The parameters that configure the retraction are retraction distance and speed. During this round of tests, it was observed that retraction could possibly cause nozzle blockage, so it was de-activated. Important note, the second test system that offers a direct drive filament supply method (extruder motor is located just before the hot end) is less prone to such clogs as it requires less retraction distance.

Anyway, retraction was not expected to provide any quality improvement because of the higher melt viscosity. Regarding printing velocity, the test range was set between 30 and 80mm/s, in 10mm/s steps. Due to the enhanced thermal conductivity of the composite material, it was expected that higher printing velocities were feasible. The latter was not succeeded due to nozzle blockages observed at these velocities. That behavior can be attributed to the increased melt pressure. Figure 21 presents two unsuccessfully (upper section) and two successfully (lower section) 3D printed samples.

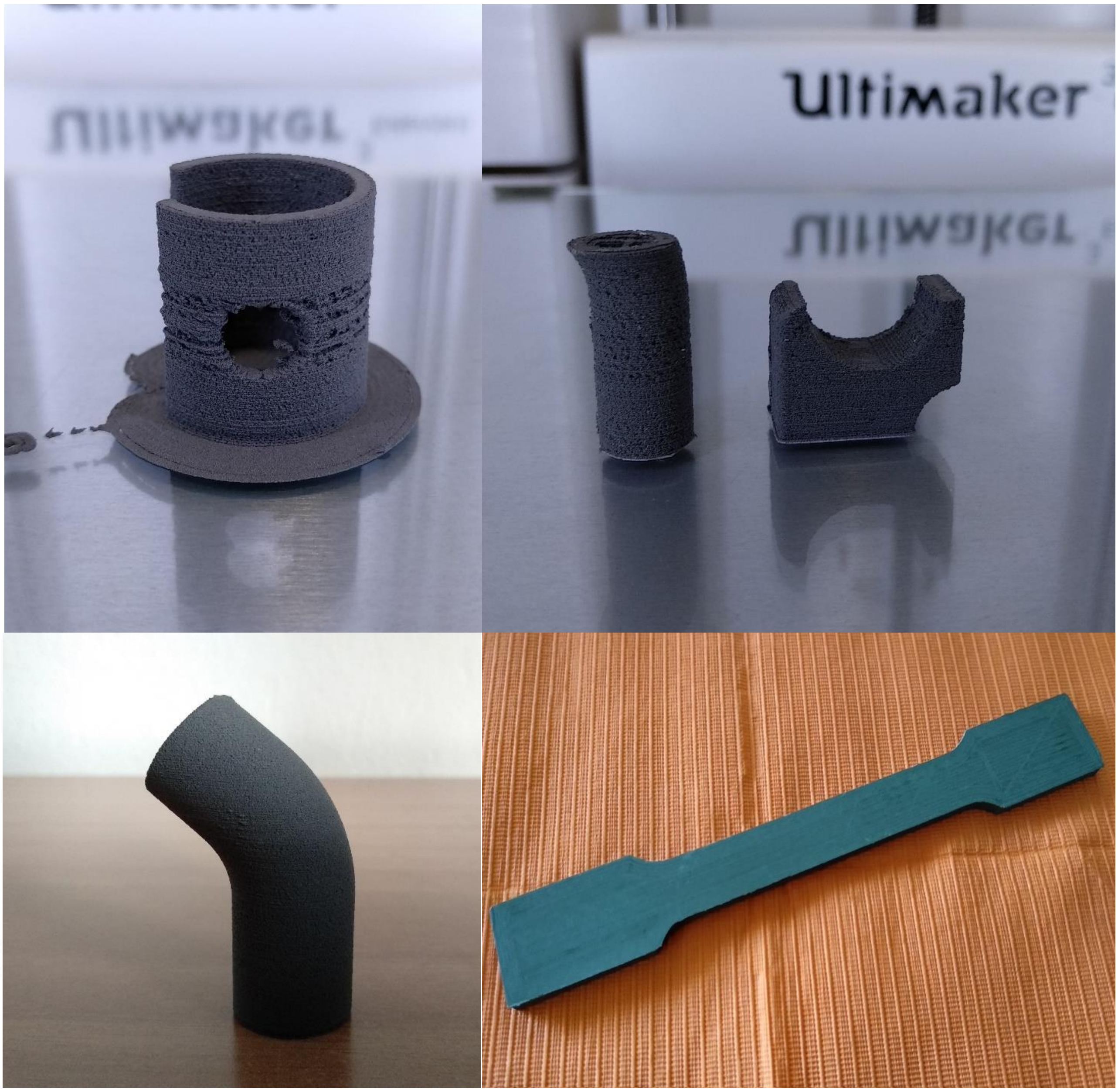


Figure 26. Upper section: Unsuccessful 3D printing parts, Lower section: Successfully 3D printed parts using optimized parameters.

This still ongoing testing methodology also includes

a. the printing of various test models to adjust printing parameters and verify printability on each different setting

b. printing of a standard 150mm Tensile Test Speciment "dogbone" 3D model according to ISO6892-1 that specifies the method for tensile testing of metallic materials and defines the mechanical properties which can be determined at room temperature.

c. printing of 20x20x20mm calibration cubes that will be later sintered to determine the material shrinkage on each axis (XYZ) as it is not linear. This would help in determining the compensation scale factor needed in the 3D models before printing to get accurate parts after the sintering process.

In all cases the tests were conducted repeatedly so that each scenario got verified and considered valid

Reference		**Printing parameters**				**Nozzle**		**Result**	
ID	**Filament material**	**Specimen geometry**	**Speed [mm/s]**	**Layer height [mm]**	**Extruder temperature [°c]**	**Material**	**Diameter**	**Pass/ Fail**	**Notes**
I3DU_1	80% 316L + PLA	Tensile.Spec	30	0.25	180	Brass	0.8	Fail	Filament grinding - bad flow
I3DU_2	80% 316L + PLA	Tensile.Spec	30	0.25	190	Brass	0.8	Fail	Filament grinding - bad flow
I3DU_3	80% 316L + PLA	Tensile.Spec	30	0.25	200	Brass	0.8	Fail	Filament grinding - bad flow
I3DU_4	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass	0.8	Pass	-
I3DU_5	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass	0.8	Pass	-
I3DU_6	80% 316L + PLA	Tensile.Spec	30	0.25	230	Brass	0.8	Pass	-
I3DU_7	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass	0.4	Fail	Nozzle blockage
I3DU_8	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass	0.5	Fail	Nozzle blockage
I3DU_9	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass	0.6	Fail	Nozzle blockage
I3DU_10	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass	0.6	Pass	-

I3DU_11	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass	0.8	Pass	-
I3DU_12	80% 316L + PLA	Tensile.Spec	40	0.25	210	Brass	0.8	Pass	-
I3DU_13	80% 316L + PLA	Tensile.Spec	50	0.25	210	Brass	0.8	Pass	Partial nozzle blockage
I3DU_14	80% 316L + PLA	Tensile.Spec	60	0.25	210	Brass	0.8	Fail	Nozzle blockage
I3DU_15	80% 316L + PLA	Tensile.Spec	70	0.25	210	Brass	0.8	Fail	Nozzle blockage
I3DU_16	80% 316L + PLA	Tensile.Spec	80	0.25	210	Brass	0.8	Fail	Nozzle blockage

Table 1. Summary of the tested 3D printing parameters of the FDM process using 2.85mm filament with metallic particles (316L)

Reference		Printing parameters				Nozzle		Result	
ID	Filament material	Specimen geometry	Speed [mm/s]	Layer height [mm]	Extruder temperature [°c]	Material	Diameter	Pass/ Fail	Notes
3DHUB_SS1	80% 316L + PLA	Tensile.Spec	30	0.25	180	Brass Nickel Plated	0.8	Fail	Filament grinding - bad flow
3DHUB_SS2	80% 316L + PLA	Tensile.Spec	30	0.25	190	Brass Nickel Plated	0.8	Fail	Filament grinding - bad flow
3DHUB_SS3	80% 316L + PLA	Tensile.Spec	30	0.25	200	Brass Nickel Plated	0.8	Fail	Partial nozzle blockage
3DHUB_SS4	80% 316L + PLA	Tensile.Spec	30	0.25	210	Brass Nickel Plated	0.8	Pass	-
3DHUB_SS5	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass Nickel Plated	0.8	Pass	-
3DHUB_SS6	80% 316L + PLA	Tensile.Spec	30	0.25	230	Brass Nickel Plated	0.8	Pass	-
3DHUB_SS7	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass Nickel Plated	0.4	Fail	Nozzle blockage
3DHUB_SS8	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass Nickel Plated	0.6	Pass	-

3DHUB_SS9	80% 316L + PLA	Tensile.Spec	40	0.25	220	Brass Nickel Plated	0.6	Pass	-
3DHUB_SS10	80% 316L + PLA	Tensile.Spec	50	0.25	220	Brass Nickel Plated	0.6	Pass	Partial nozzle blockage
3DHUB_SS11	80% 316L + PLA	Tensile.Spec	60	0.25	220	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_SS12	80% 316L + PLA	Tensile.Spec	70	0.25	220	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_SS13	80% 316L + PLA	Tensile.Spec	80	0.25	220	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_SS14	80% 316L + PLA	Tensile.Spec	30	0.25	220	Brass Nickel Plated	0.8	Pass	-
3DHUB_SS15	80% 316L + PLA	Tensile.Spec	40	0.25	220	Brass Nickel Plated	0.8	Pass	-
3DHUB_SS16	80% 316L + PLA	Tensile.Spec	50	0.25	220	Brass Nickel Plated	0.8	Pass	Partial nozzle blockage
3DHUB_SS17	80% 316L + PLA	Tensile.Spec	60	0.25	220	Brass Nickel Plated	0.8	Fail	Nozzle blockage
3DHUB_SS18	80% 316L + PLA	Tensile.Spec	70	0.25	220	Brass Nickel Plated	0.8	Fail	Nozzle blockage
3DHUB_SS19	80% 316L + PLA	Tensile.Spec	80	0.25	220	Brass Nickel Plated	0.8	Fail	Nozzle blockage

Table 2. Summary of the tested 3D printing parameters of the FDM process using 1.75 filament with Stainless Steel 316L metallic particles

H2020 Innovation Action - This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N. 760792

Reference		Printing parameters				Nozzle		Result	
ID	Filament material	Specimen geometry	Speed [mm/s]	Layer height [mm]	Extruder temperature [°c]	Material	Diameter	Pass/ Fail	Notes
3DHUB_CP1	88% COPPER + PLA	Tensile.Spec	30	0.25	180	Brass Nickel Plated	0.8	Fail	Filament grinding - bad flow
3DHUB_CP2	88% COPPER + PLA	Tensile.Spec	30	0.25	190	Brass Nickel Plated	0.8	Fail	Filament grinding - bad flow
3DHUB_CP3	88% COPPER + PLA	Tensile.Spec	30	0.25	200	Brass Nickel Plated	0.8	Fail	Filament grinding - bad flow
3DHUB_CP4	88% COPPER + PLA	Tensile.Spec	30	0.25	210	Brass Nickel Plated	0.8	Fail	Partial nozzle blockage
3DHUB_CP5	88% COPPER + PLA	Tensile.Spec	30	0.25	220	Brass Nickel Plated	0.8	Pass	-
3DHUB_CP6	88% COPPER + PLA	Tensile.Spec	30	0.25	230	Brass Nickel Plated	0.8	Pass	-
3DHUB_CP7	88% COPPER + PLA	Tensile.Spec	30	0.25	230	Brass Nickel Plated	0.4	Fail	Nozzle blockage
3DHUB_CP8	88% COPPER + PLA	Tensile.Spec	30	0.25	230	Brass Nickel Plated	0.6	Pass	-
3DHUB_CP9	88% COPPER + PLA	Tensile.Spec	40	0.25	230	Brass Nickel Plated	0.6	Pass	-
3DHUB_CP10	88% COPPER + PLA	Tensile.Spec	50	0.25	230	Brass Nickel Plated	0.6	Pass	Partial nozzle blockage
3DHUB_CP11	88% COPPER + PLA	Tensile.Spec	60	0.25	230	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_CP12	88% COPPER + PLA	Tensile.Spec	70	0.25	230	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_CP13	88% COPPER + PLA	Tensile.Spec	80	0.25	230	Brass Nickel Plated	0.6	Fail	Nozzle blockage
3DHUB_CP14	88% COPPER + PLA	Tensile.Spec	30	0.25	230	Brass Nickel Plated	0.8	Pass	-

3DHUB_CP15	88% COPPER + PLA	Tensile.Spec	40	0.25	230	Brass Nickel Plated	0.8	Pass	-
3DHUB_CP16	88% COPPER + PLA	Tensile.Spec	50	0.25	230	Brass Nickel Plated	0.8	Pass	-
3DHUB_CP17	88% COPPER + PLA	Tensile.Spec	60	0.25	230	Brass Nickel Plated	0.8	Fail	Partial nozzle blockage
3DHUB_CP18	88% COPPER + PLA	Tensile.Spec	70	0.25	230	Brass Nickel Plated	0.8	Fail	Nozzle blockage
3DHUB_CP19	88% COPPER + PLA	Tensile.Spec	80	0.25	230	Brass Nickel Plated	0.8	Fail	Nozzle blockage

Table 3. Summary of the tested 3D printing parameters of the FDM process using 1.75 filament with Copper metallic particles

Figure 27. Test setup and 3D printed test models

5. CONCLUSION

The appropriate specifications and concept design are due to the numerous tests taken with the recovered materials and powders received. Exhaustive studies in the field of mechanics have provided very useful results to determine the technical specifications of the machine. Moreover, the study of the functionality of a commercial DIW equipment (BIO X 3D BIOPRINTER, Cellink) has allowed to set the concept needed in the DIW printer developed in this project.

In relation with the detail design and fabrication process, some parts of the DIW system are already assembled, but other ones are still in the conceptual design phase, as the humidity and temperature control system.

For the DIW part, the device described in task 3.5 is functional and ready to operate in the pilot plant. The validation tests have demonstrated the necessity of a more accurate temperature control. Once the humidity and temperature control systems are assembled to the rest of the machine, more accurate validation tests will be able to be carried out and will allow the study and obtaining better results.

The addition of particles to the FDM filament was successful and allowed to print several good quality parts. However, the success rate of the prints is still low, due mainly to blockages of the nozzle by the particles, some improvements can still be made in this regard.