# Inductive thermal effect on thermoplastic nanocomposites with magnetic nanoparticles for self-healing, bonding and debonding on demand applications

Kanidi M. , Loura N., Frengkou A., Kosanovic T., Trompeta A. F. & Charitidis C.

Research Lab of Advanced, Composite, Nanomaterials and Nanotechnology (R-NanoLab)

School of Chemical Engineering

National Technical University of Athens

SmartFAN

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# Outline

- General aspects
- Production of nanocomposite filament
- Compounding
- Materials characterization
- Functionality testing
- Healing properties
- Bonding and debonding on demand applications
- Conclusions

# Motivation

- Plastic **circularity** & Reduce plastic scrap
- **Extend end of life** of products
- Enable **easy repair**

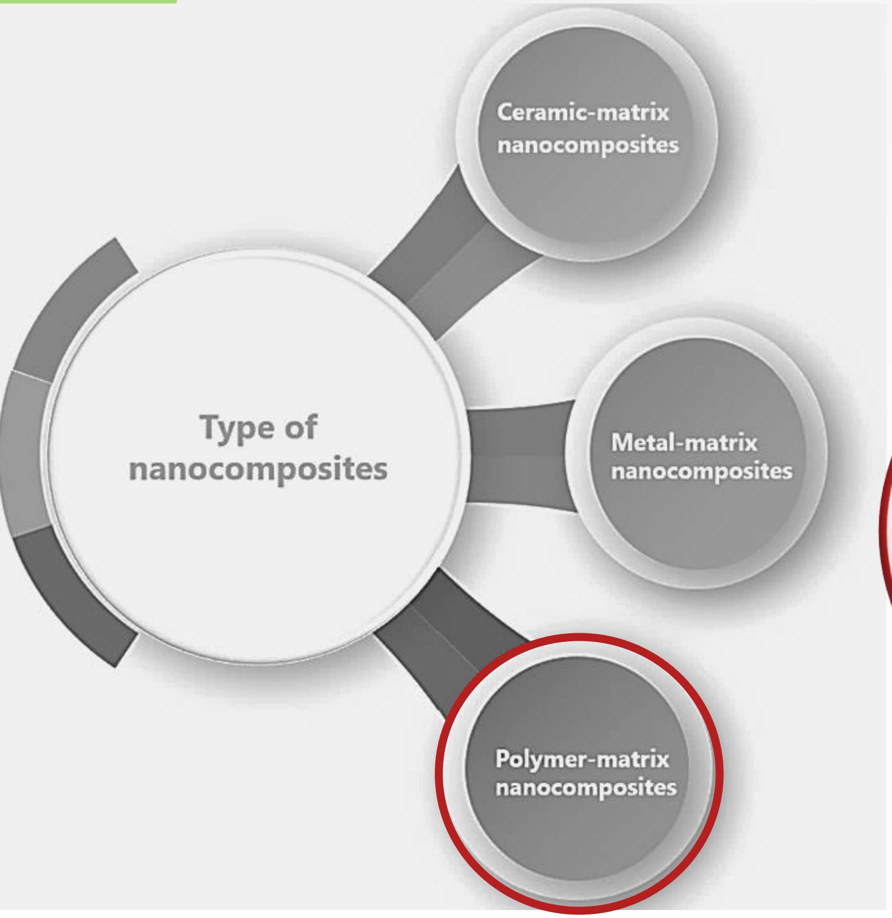
- Inductive thermal effect

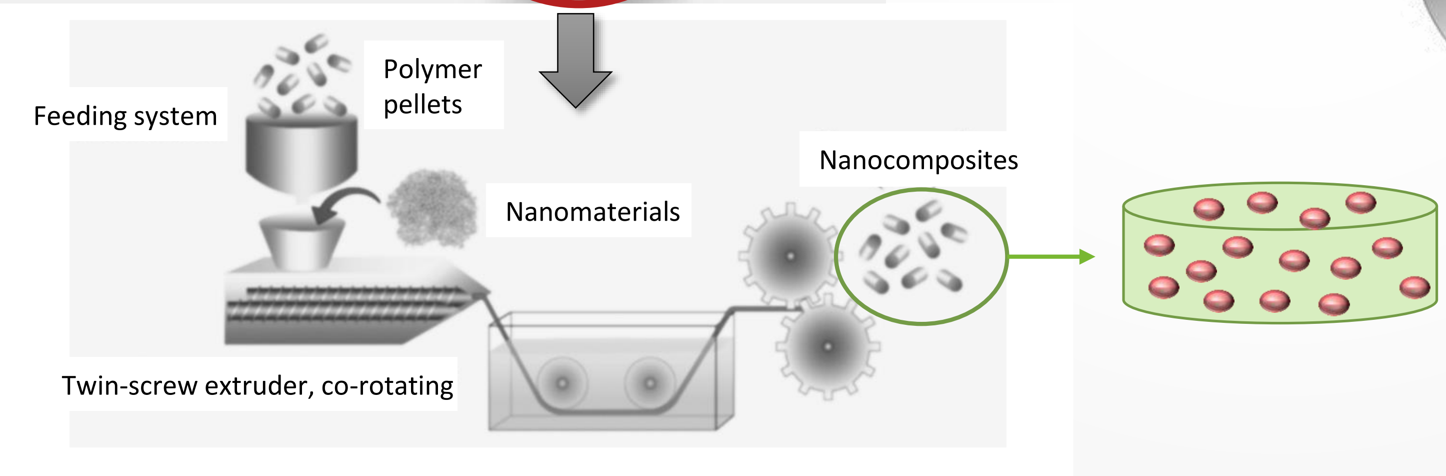
  - **cost-competitive** products by implementing Circular Economy concepts

  - reversible joining procedures, providing **easy-to-disassembly operations**

  - design time, scrap, weight, and Maintenance, Repair and Overhaul (MRO) **cost reductions**

- **Design for recycling** principles
- End of Life **disassembly - repair**



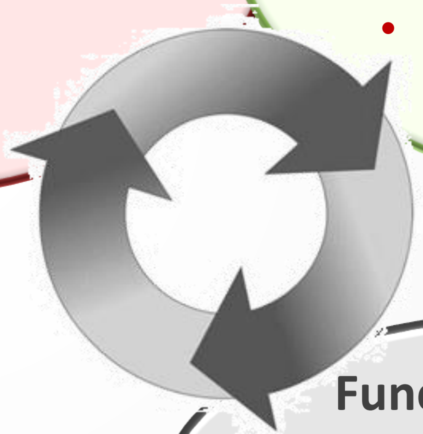




**Nanomaterials:**

- Nanoparticles
- Nanowires/nanorods
- Nanofilms
- Carbon nanotubes
- Fullerene
- Graphene

**Nanotechnology:**

- Energy and environment
- Transportation and aerospace
- Textiles & clothing
- Information technology
- Agriculture
- Healthcare & Medicines

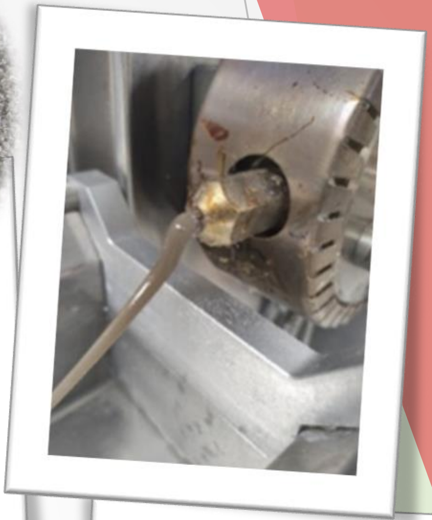


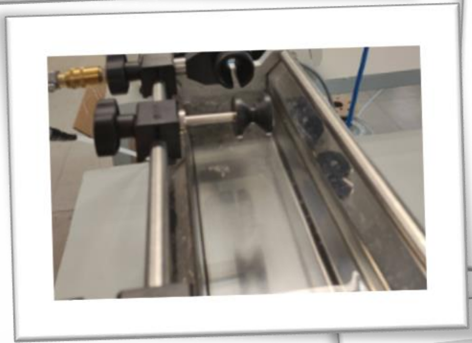
**Functional properties**

Healing behavior

Bonding and debonding on demand

# Extrusion process - Compounding





- Extrusion system: twin screw extruder, co-rotating

- Feeder –Melt pump - Cooling bath – Laser monitoring – Winding system

- Optimizing process parameters: temperature profile, screw speed, pressure etc.

| Temperature zones (°C) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Screw speed (rpm) | Feeder speed (rpm) |
|---|---|---|---|---|---|---|---|---|---|
| **PP** | 200 | 200 | 200 | 200 | 190 | 180 | 120 | 400 | 42 |
| **PA12** | 225 | 225 | 225 | 200 | 200 | 180 | 100 | 400 | 50 |
| **TPU** | 210 | 210 | 210 | 210 | 200 | 180 | 105 | 350 | 30 |
| **PEKK** | 323 | 323 | 310 | 310 | 305 | 305 | 290 | 200 | 8 |

# Extrusion process - Compounding

- Thermoplastic matrices compounded with $Fe_3O_4$ nanoparticles (20 nm diameter)
- Trials with several concentrations of magnetic nanoparticles
- Samples preparation for functionality testing:

  3D printed, thermopressed, injection molded

| Matrix | Concentration % wt. MNPs | Type of sample |
|---|---|---|
| **PP** | 2.5, 5, 7.5, 10 | 3D printed |
| **PA12** | 2.5, 5, 7.5, 10 | 3D printed |
| **TPU** | 2.5, 5, 7.5, 10 | thermopressed |
| **PEKK** | 2.5, 5, 7.5, 10 | Injection molded |

# Characterization:
# Thermal analysis -TGA

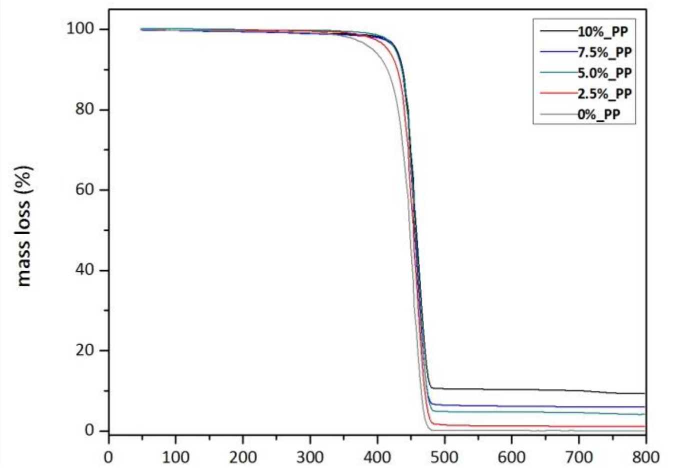
***PP nanocomposites***

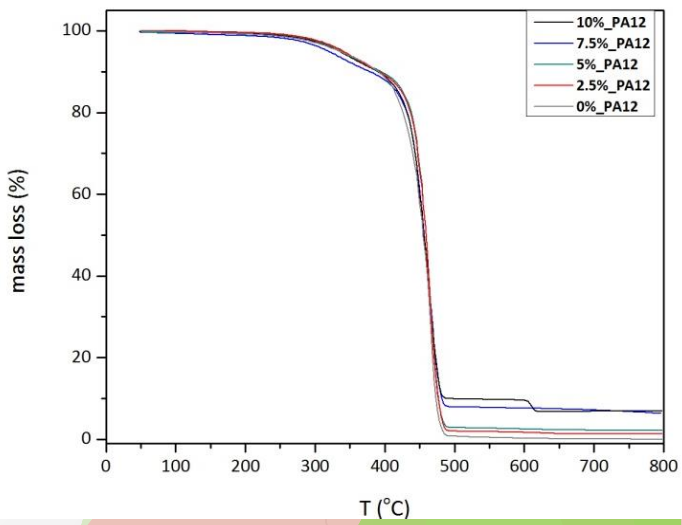
- Onset temperature of decomposition demonstrated an increasing trend - dependence on the content of magnetic nanoparticles.
- The residual mass follows an increasing trend with magnetic nanoparticles content.
- In all cases it is smaller compared to the original weight ratio.

***PA12 nanocomposites***

- MNPs do not affect at all the thermal decomposition behavior of the nanocomposites.
- The nominal weight ratio deviates from the percentage of the final mass.
- Possible gradients in composition, due to the dispersion process and melt-spinning.

| Identity | sample mass (mg) | Residual mass (%) | Residual mass – matrix contribution (%) |
|---|---|---|---|
| **PP_0 %** | 18.2 | 0 | - |
| **PP_2.5 %** | 18.2 | 1.1 | 1.1 |
| **PP_5 %** | 17.8 | 3.9 | 3.9 |
| **PP_7.5 %** | 20.6 | 6.1 | 6.1 |
| **PP_10 %** | 19.8 | 9.4 | 9.4 |
| **PA12_0 %** | 18.4 | 0 | - |
| **PA12_2.5 %** | 20.0 | 1.2 | 1.2 |
| **PA12_5 %** | 15 | 2.2 | 2.2 |
| **PA12_7.5 %** | 19.1 | 7.1 | 7.1 |
| **PA12_10 %** | 16.1 | 8.5 | 8.5 |



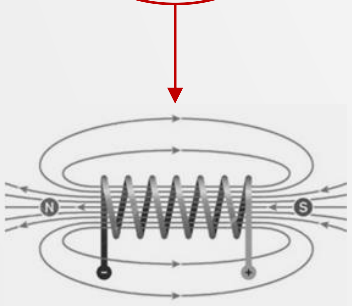
# Induction heating technology

- **Induction heating** is the process of heating electrically conductive materials by electromagnetic induction.
- Heat is transferred by an **induction coil** that creates an electromagnetic field around the coil, with the same frequency.

**Induction heating:**

- Improved process efficiency
- Localized, constant and precise heating
- Temperature control
- Energy saving
- Possibility to integrate into production lines
- Pollution free, fast and secure technology
- Improved working environment

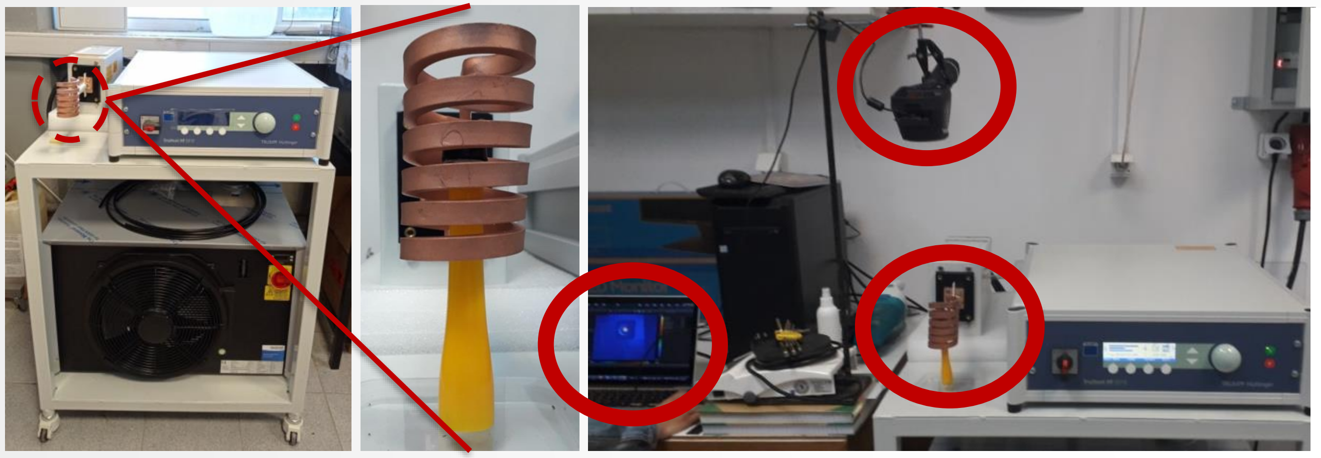

- The field generated by the induction coil influences the heating patterns of the susceptors and the field is a function of the **coil geometry**.

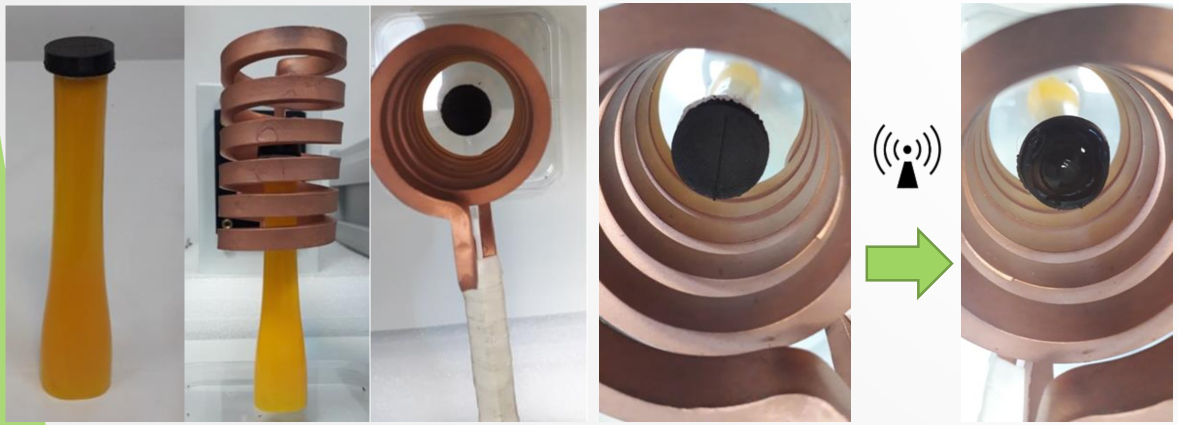


**Mechanism of hysteresis loss**

Magnetic nanoparticles ($Fe_3O_4$): susceptor materials generate heat by hysteresis for polymer adhesive joining processes and thermoplastic healing.

# Induction heating set up

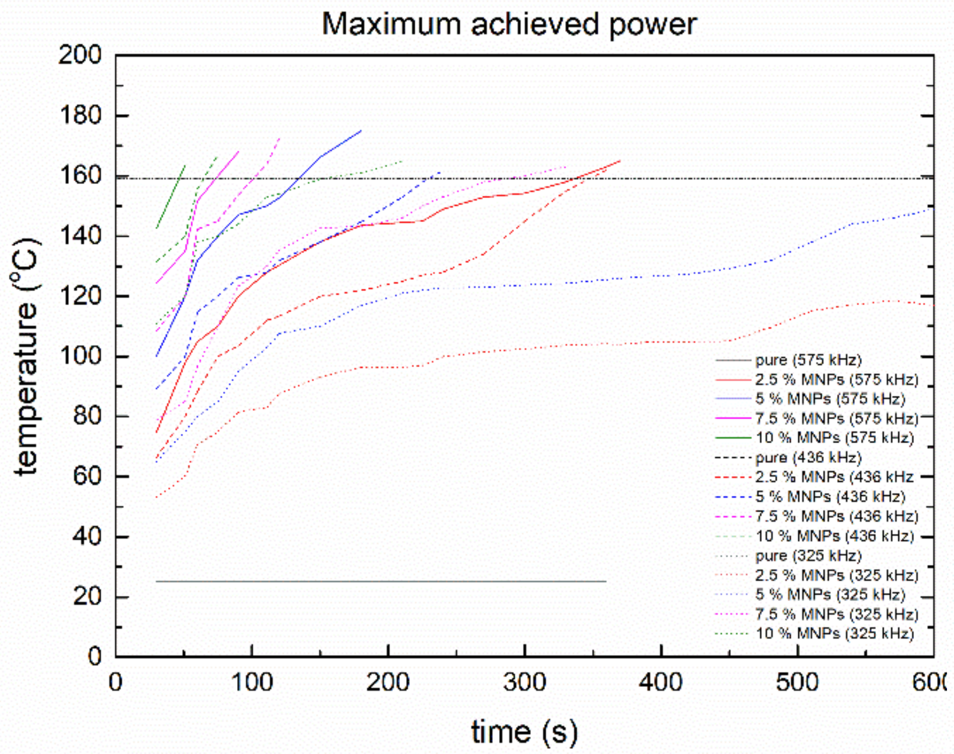


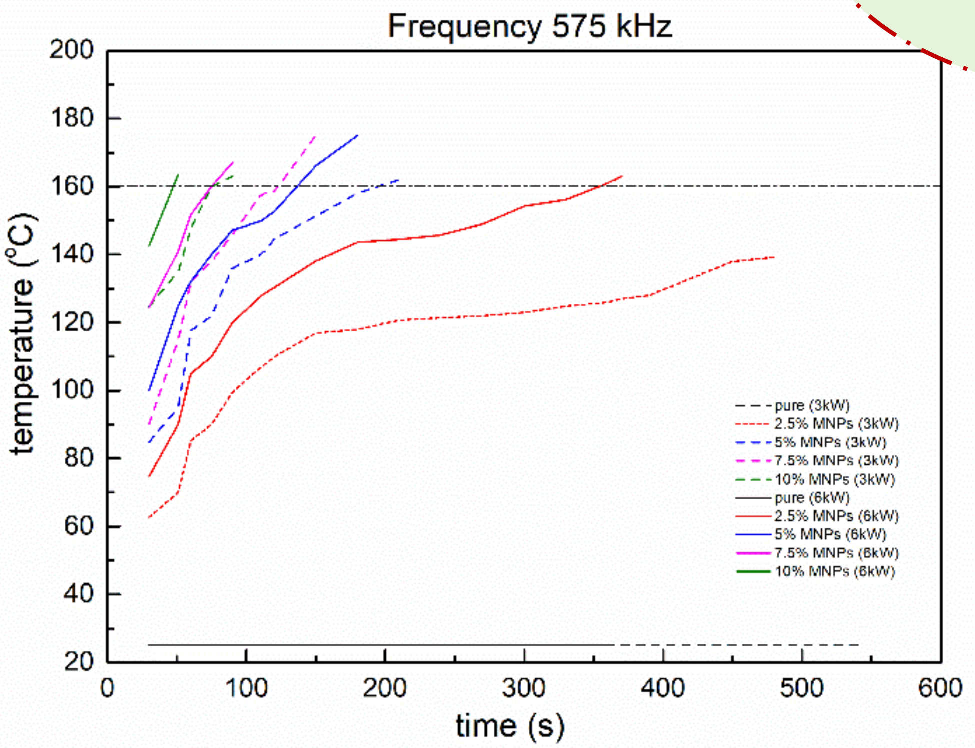


- RF Generator TruHeat HF 5010 (max Power: 10 kW, max Current: 35 A, Input Voltage: 600 V)
- The maximum permissible RF current depends on the respective operating frequency.
- The permissible operating parameters of the currently used capacitors in the series oscillator circuit and available coil: 350, 450 & 575 kHz
- Inductor coil: solenoid geometry, H = 8.5 cm and inner D = 4.5 cm
- Thermo-camera: Flir (maximum T = 400ºC)
- Monitoring software Flir Tools+

# Induction heating process window

- Heating capacity of PP nanocomposites
- Investigation of process window

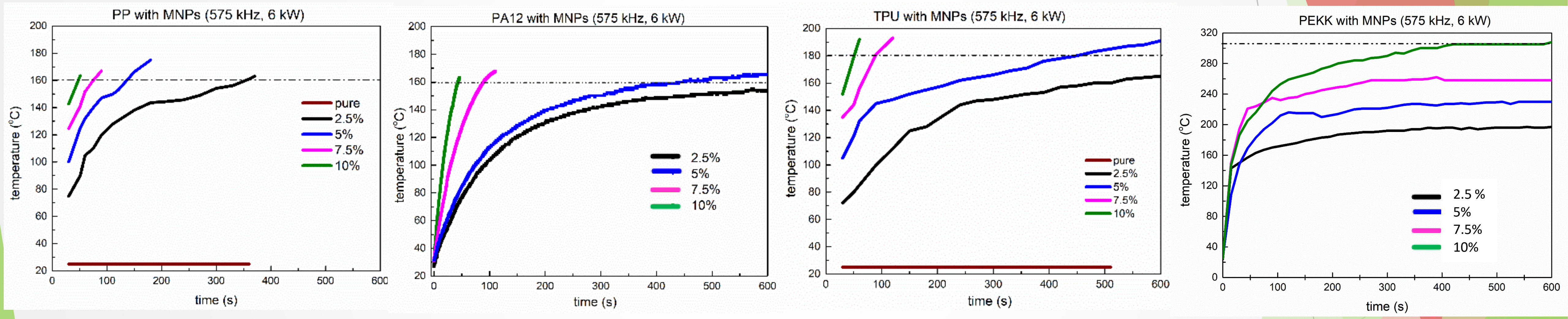



- Increasing frequency on the maximum power results in higher temperatures.
- Increasing power results in higher temperatures.
- Heating capacity is proportional to the RF frequency and power with the current coil geometry.

# Heating capacity of TP nanocomposites

- Heating capacity of PP, PA12, TPU & PEKK nanocomposites
- Optimum operating RF conditions (575 kHz & 6 kW)




- ➢ Temperature increase is proportional to MNPs concentration for all TP matrices.
- ➢ Nanocomposites with lower MNPs concentration require longer exposure time to increase temperature.

# Inductive thermal effect

**Healing properties**

**PP, PA12, TPU**

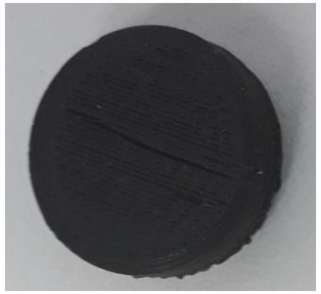
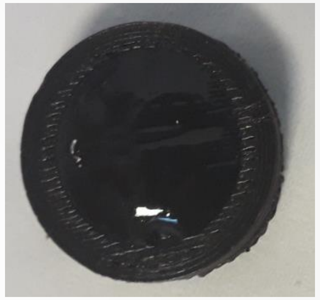
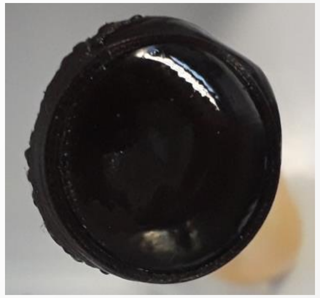
Repair

**Bonding and Debonding on demand**

**PEKK**

Disassembly on demand

# Healing behavior

| PP nanocomposites | | | PA12 nanocomposites | |
|---|---|---|---|---|
| Before induction heating | After induction heating | | Before induction heating | After induction heating |
|  |  | 7.5 % wt. $Fe_3O_4$ |  |  |
|  |  | 10 % wt. $Fe_3O_4$ |  |  |

- Healing behavior is observed in most polymer matrices embedded with MNPs.
- Healing time is proportional to the MNPs concentration.
- Induction heating technology can be suitable technique to heat preferentially joint materials in order to bond and/or debond on demand

# Bonding and debonding on demand
# Heating capacity of PEKK

High performance polymer ($T_g$ 160 °C, $T_m$ 305 °C)
- able to work at high temperatures
- high chemical and oxidation resistance
- Suitable for composite structural parts for aerospace applications

PEKK nanocomposites

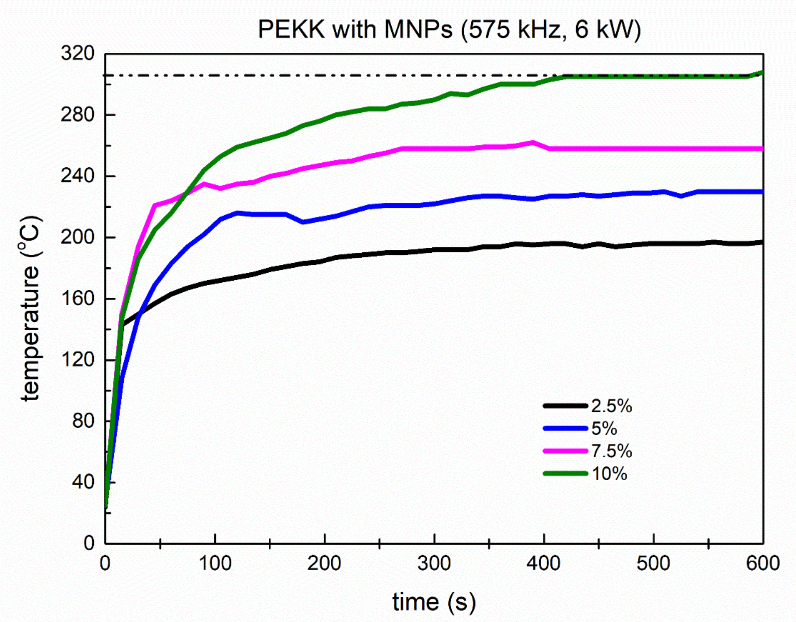
Before induction heating | After induction heating

10 % wt. $Fe_3O_4$

7.5 % wt. $Fe_3O_4$

5 % wt. $Fe_3O_4$

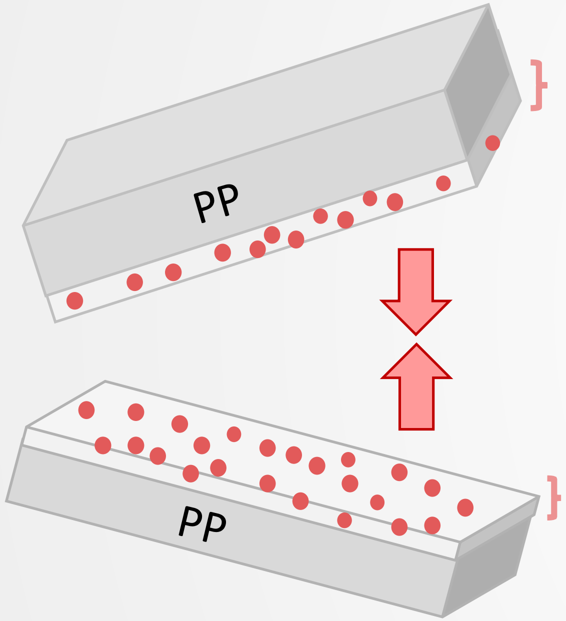
2.5 % wt. $Fe_3O_4$




- PEKK nanocomposites do not reach the $T_m$ for all MNPs concentration.
- Only PEKK with 10% wt. MNPs is heated ~ 305 °C.
- Heated above $T_g$, shape reformation is allowed.

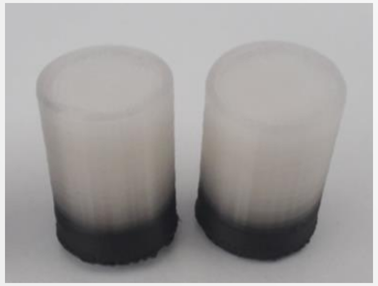
# Bonding on demand

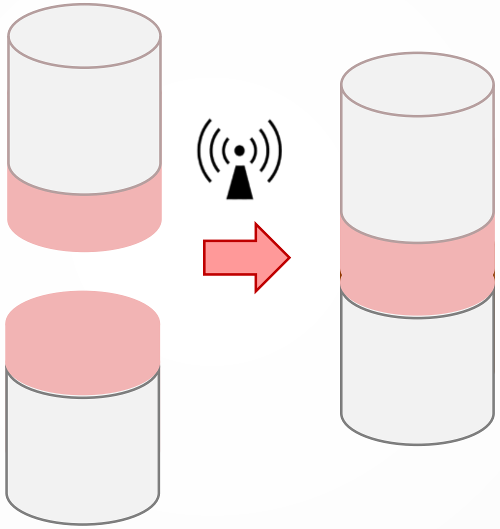
- PP components are heated though induction heating and bonded by applying pressure

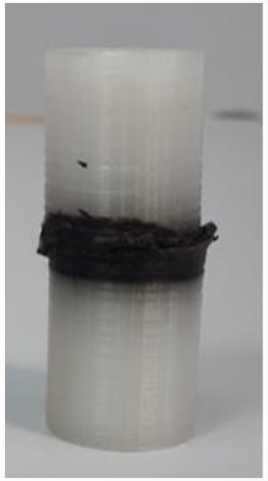



PP-10wt% $Fe_3O_4$

PP-10wt% $Fe_3O_4$

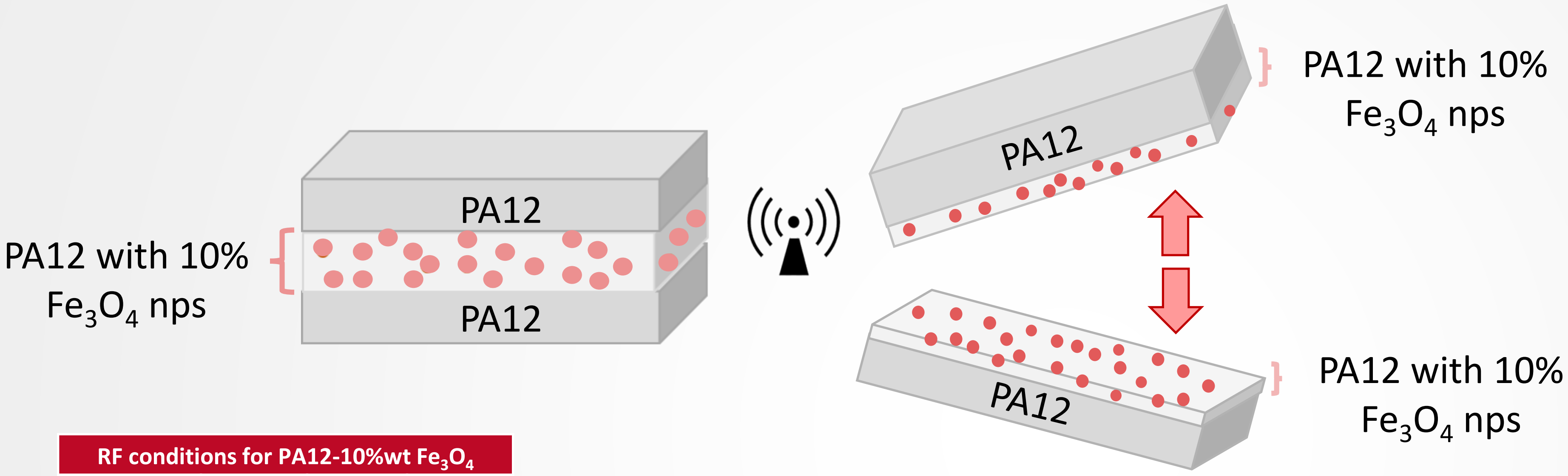




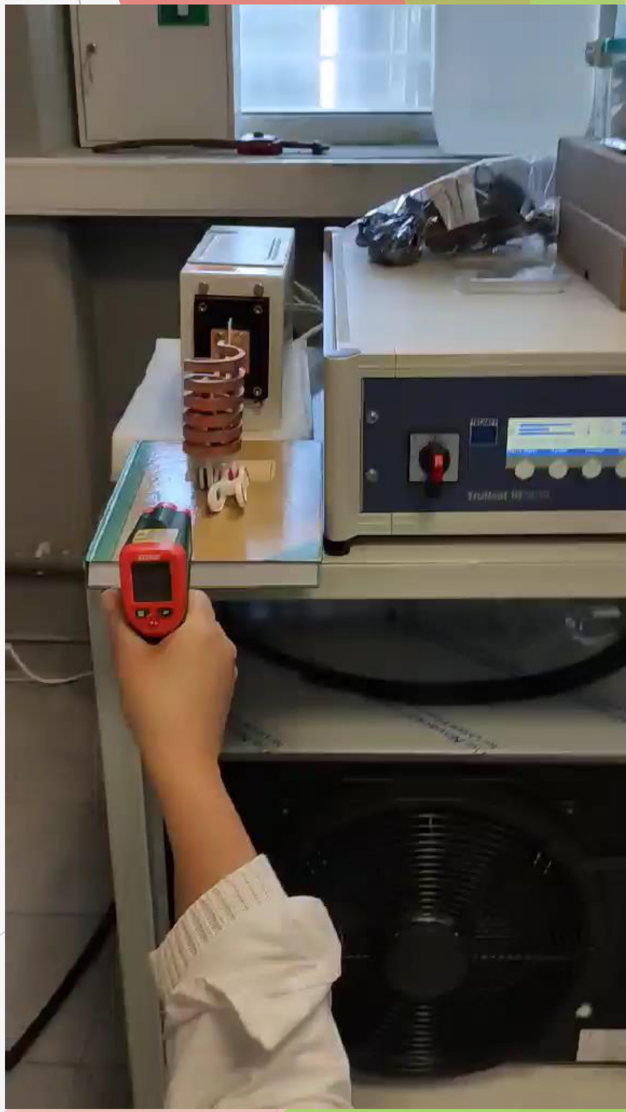


| RF conditions for PP-10%wt $Fe_3O_4$ | | | |
|---|---|---|---|
| Frequency [kHz] | Power [kW] | Time [s] | Temp. [$^{o}$C] |
| 575 | 6 | 30 | 145 |

# Debonding on demand



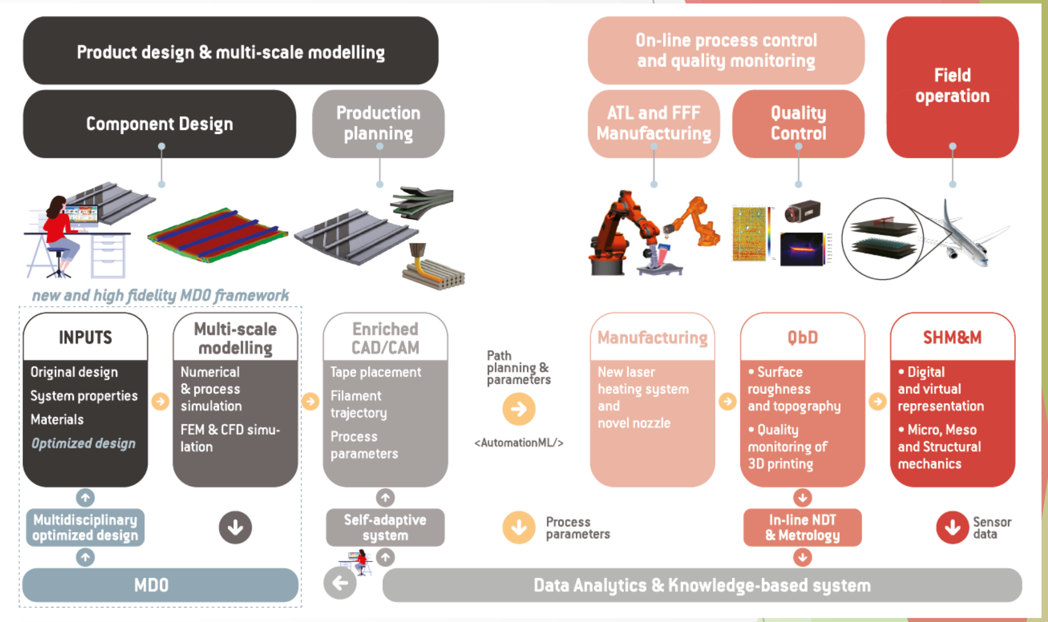

| RF conditions for PA12-10%wt $Fe_3O_4$ | | | |
|---|---|---|---|
| Frequency [kHz] | Power [kW] | Time [s] | Temp. [ºC] |
| | | 60 | 42.4 |
| | 2 | 90 | 60 |
| | | 120 | 60.8 |
| | | 30 | 69.9 |
| | | 90 | 84.8 |
| 575 | 4 | 150 | 103 |
| | | 180 | 117.5 |
| | | 240 | 126.8 |
| | | 60 | 60 |
| | 6 | 120 | 93 |
| | | 180 | 140 |



# Conclusions

- Nanocompounding through extrusion is an efficient process to produce **nanocomposites with desired properties**.
- Inductive thermal effect offers localized, constant and precise preferentially heating of thermoplastic nanocomposites in order to **bond and/or debond on demand**.
- Reaching temperatures close to the $T_m$ of thermoplastic matrices, nanocomposites present **healing behavior**, **reducing repair costs**.
- Induction heating is a promising technology for **repairing** thermoplastic matrices enabling **recycling** and bonding/debonding on demand applications for the development of **sustainable materials**.

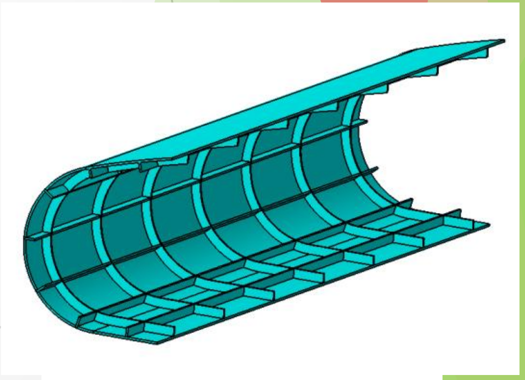
**D**igital method for impr**O**ved **M**anufacturing of next-generation **M**ult**I**fu**N**ct**IO**nal airframe parts




DOMMINIO aims to:

- Enable **flexible multistage robotic-based production** processes for manufacturing of multifunctional composite airframe parts
- Develop **novel data-driven pipeline** supporting the design, simulation and production planning of multifunctional and intelligent composite airframe components.
- Develop a **Quality-by-Design** (QbD) manufacturing strategy, based on the development of process control and **advanced quality monitoring systems**.
- Develop **a new digital-combined-physical driven methodology** for Monitoring and Management of the Health of multifunctional airframe parts.

**multifunctional airframe access panel**

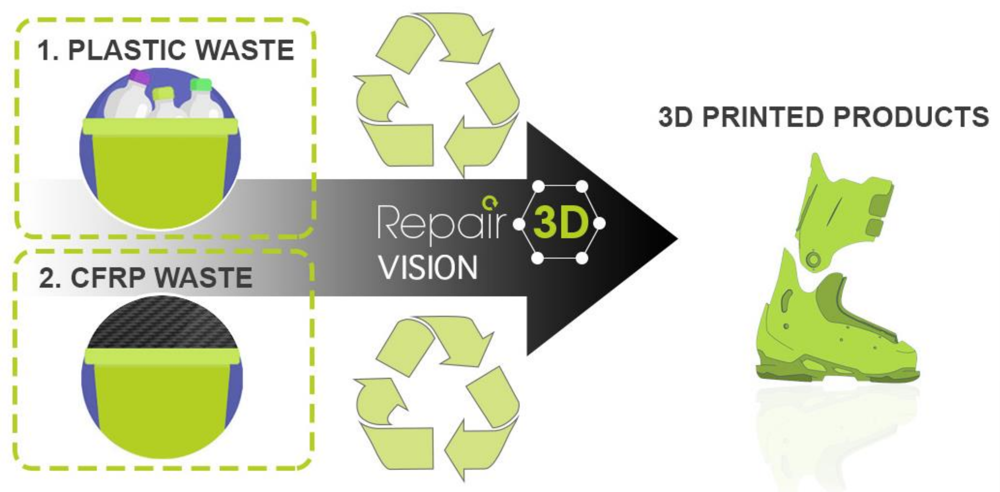


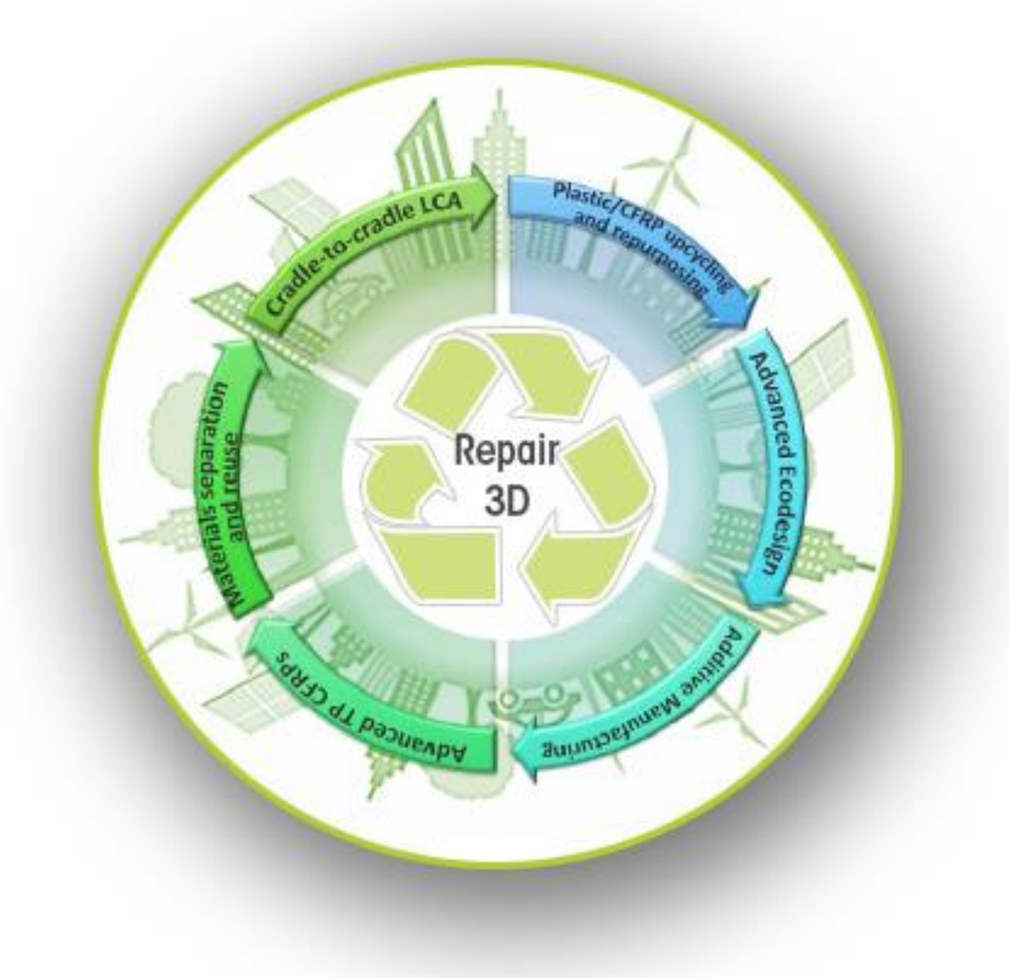
**wing leading edge**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007022.

Recycling and Repurposing of Plastic Waste for Advanced 3D Printing Applications

Repair3D aims at the development of innovative reclamation and repurposing routes for **end-of-life plastic** and carbon fibre reinforced polymer (**CFRP**) components by employing **advanced nanotechnology solutions**, Additive Manufacturing and **recycled resources**, for the production of high **added value 3D printed products** with advanced functionalities.




This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 814588.

# European Union's Horizon 2020 research and innovation programs

domminio

Digital method for improved manufacturing of next-generation multifunctional airframe parts

https://domminioproject.eu

Repair3D

https://www.repair3d.net/

## RNano Lab – NTUA team

# Thank you

# Ευχαριστώ

Prof. Costas Charitidis
charitidis@chemeng.ntua.gr
http://nanolab.chemeng.ntua.gr/

Dr. Maria Kanidi
mkanidi@chemeng.ntua.gr