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Additive foam manufacturing

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Abstract. Traditional foams manufacturing processes are used to create quickly and cost-effectively high-strength and low-weight structures; lately there have been efforts to produce foams in Additive Manufacturing (AM), making it possible to produce free-form foamed structures. One of the biggest advantages of the additive foam manufacturing (AFM) technique proposed in this paper is the use of a physical blowing agent (PBA), which, as opposed to a chemical blowing agents (CBA), can be used to foam almost any thermoplastic polymer without modifying its chemical properties, resulting in a polymer life-cycle advantage, especially from the recycling point of view. The research being presented aims to investigate the effect of process parameters on the microstructure and properties of 3D printed physical foams, in terms of density, dimensions and mechanical properties.

Introduction

Polymer cellular materials are used in several applications and technological fields (e.g., biomedical, engineering, aerospace, nautical, sport and leisure), offering distinctive characteristics that derive from their cellular morphology and pores structures (i.e., dimension, orientation, density) [1]. Many examples are also present in nature where high performances are reached at minimum material cost using foams [2]. As a matter of fact, Nature has often chosen optimized cellular structures to shape life on our planet. The pores' characteristic size, shape, and organization are important factors in determining these materials' structure–property relationship. Natural cellular materials, such as echinoid and beeswax honeycombs [3, 4], are usually complex foamed structures, designed to carry out a specific task or optimize a specific property. The development of AM made it feasible to increase the design potentials of a component: generative design and lattice structures are only few of the instruments which allow to improve the performances of highly engineered parts for specific mechanical properties, with high strength-to-relative-density ratio. However, incorporating lattice structures into the design of an object can be challenging, as it requires careful consideration of multiple design parameters and introduces complexities in predicting the resulting mechanical behavior. [5]. Nowadays foams could be easily and cost-effectively produced by AM technology with control over micro and macro morphology thanks to an innovative foam AM (FAM) that has been developed by Tammaro et al. [6], by pre-treating the filament with a physical blowing agent (PBA).

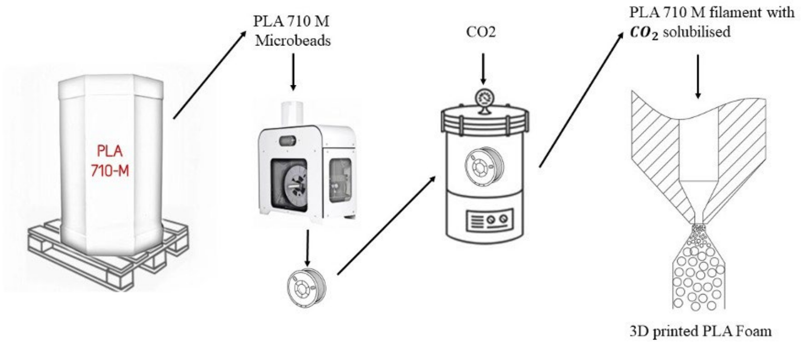


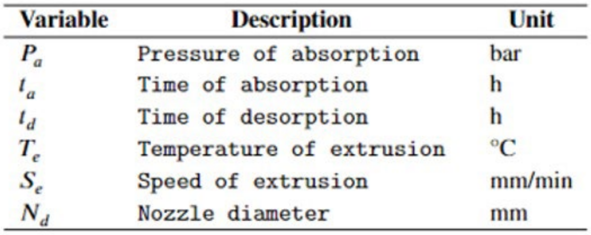
Figure 1 Schematic representation of the steps in a FAM process

During the fused filament deposition (FFM) the PBA expands creating bubbles in the polymer. In contrast with CBA, it can be used to foam almost any thermoplastic polymer without altering the chemical composition. This turns out in a polymer life-cycle advantage, especially from the point of view of its recycling. Nofar et al. [7] reviewed the influences of the main FAM parameters on the foam properties. FAM process consists of two phases: solubilization and extrusion. In the first phase, the solubilization, the polymeric filament is kept in a autoclave in which the PBA is insufflated by controlling the pressure and the temperature of the vessel, and the time of absorption. This allows the PBA to be solubilized within the polymer filament. After this phase, if the polymer is simply stored at room condition a partial desorption of the PBA can be induced: the longer is the desorption time the higher is the percentage of lost PBA. By carefully managing the two previous phases it is possible to have a designable gradient of PBA along the cross section of the filament. The second phase consists of the extrusion through a capillary (nozzle) with the desired exit diameter, controlling the temperature and the speed of the extrusion. [8]. During the extrusion phase, the polymer experiences a rapid pressure drop and a temperature rise from the inside to the outside of the nozzle. Due to this effect, the PBA expands and causes the polymer foaming. The rapid temperature rise and expansion allow the foamed polymer to crystallize.

Process Parameters

Each of the process parameters, reported in Table 1, should be investigated to map its importance on the microstructure and the mechanical behavior of the thermoplastic polymer foam produced.

Table 1 Process parameters and their unit



Variable	Description	Unit
P_a	Pressure of absorption	bar
t_a	Time of absorption	h
t_d	Time of desorption	h
T_e	Temperature of extrusion	°C
S_e	Speed of extrusion	mm/min
N_d	Nozzle diameter	mm

The percentage of PBA solubilized in the polymer could be easily set up by changing the P_a value: the higher the P_a and the higher the PBA in the polymer. t_a and t_d values control the gradient of the concentration of the PBA in the cross-section of the foamed strand. The larger the t_a value, the deeper the PBA solubilizes in the polymer, the lower the foam density and the more the bubbles will show up toward the core. On the other hand, as the t_d value increases, the PBA tends to desorb from the polymer and the number of bubbles on the surface reduces. In the extrusion phase the polymer filament, with the PBA solubilized inside, is pushed by a gear system in the extruder. As is represented in Figure 2 the extruder consists of two zones, a heated zone, referred to as the hot end, and a cooled area, referred to as the cold end.

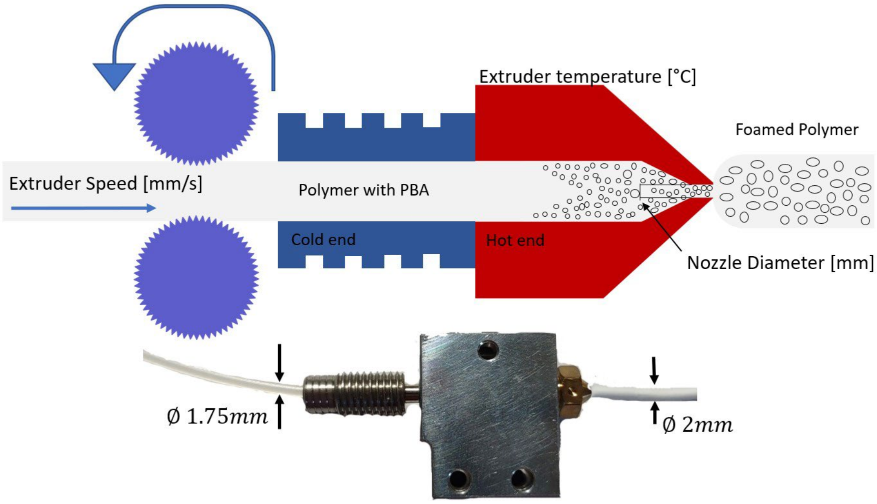


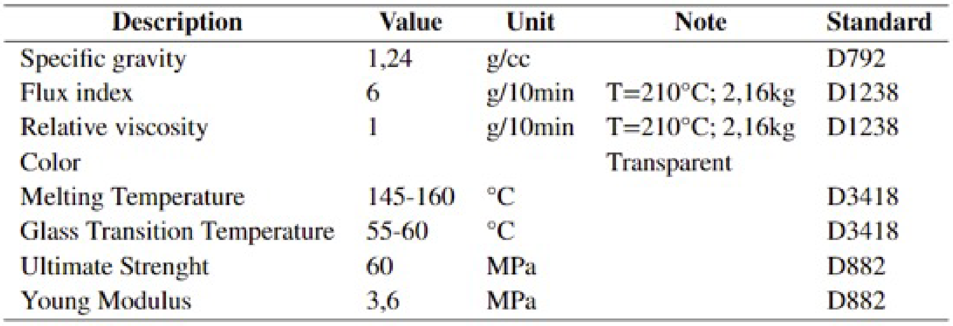
Figure 2 Additive Manufacturing of foams extruder: sketch (top) and real picture (bottom).

The hot end is a heated convergent conduit with a final capillary (nozzle) in which the polymer is melted. The cold end is the connection conduit from the gear system to the hot end, it is cooled usually with a fan system, in order to keep the temperature of the pushed filament constant and lower than the melting temperature of the polymer. In the present research, the influence of the temperature of the extruder T_e, the pushing speed of the gear system S_e, and the nozzle diameters N_d on the foam morphology and properties have been investigated. The foaming phenomenon is given to the equilibrium of two forces at the interface between the polymer and the PBA. First the PBA, previously solubilized in the polymer, tends to expand during heating. On the other hand, the polymer pushed in the nozzle from the gear system results in pressure. Inside the nozzle, the polymer pressure is predominant, and the PBA cannot expand. At the exit of the nozzle, the pressure of the polymer drops and the over-pressurized PBA quickly expands promoting the polymer foaming. The T_e performs a critical role in the viscosity of the polymer and affects the flow behaviour, as showed in [11]. Experimental studies have shown that the foam density decreases with an increase in temperature during extrusion. These relationships have been widely studied and reported in the literature on polymer extrusion and foaming. For example, [9] provide a comprehensive overview of the complex relationship between foam density and temperature. An increase in Se leads to a higher pressure of the polymer melt in the nozzle due to the increased shear rate and shear stress, consequently, the viscosity of the polymer melts decreases [10]. The geometry of the conduit Nd affects the speed, the pressure of the polymer, and the heat transfer from the nozzle to the polymer. Because the FAM is a multiphase extrusion of polymer and PBA, all the extrusion parameters have an influence on the expansion force of the PBA and on the interaction between the two. Since FAM involves the multiphase extrusion of polymer and PBA, all extrusion parameters can influence the expansion force of the PBA and the interaction between the two phases. Changes in the extrusion temperature, pressure, speed, and die geometry can alter the rheological properties of the polymer melt and the PBA, affecting, the viscosities, and interfacial tensions this led to variations in the foam morphology, cell size, and density [12]. The process results are repeatable and controllable through a statistical experimental campaign, and mutual influences of process parameters on foam morphology can be studied.

Materials and methods

In this research it was chosen to validate the AM of thermoplastic polymer foams with a custom-made polylactic acid filament, to have control of the thermal history and the rheology of the filament. Each foamed strand was then characterized in terms of microstructure with SEM images, mechanical properties via mini-tensile tests and finally in terms of density and cross section size measurements. The polylactic acid (PLA) used in this research is the PLA 710 grade M of the Bewi Synbra bought as microbeads, whose characteristics are reported from the manufacturer [13]. The carbon dioxide pure at 99,95% from the Sol Group S.p.a was used as a blowing agent.

Table 2 Polymer properties



Description	Value	Unit	Note	Standard
Specific gravity	1,24	g/cc		D792
Flux index	6	g/10min	T=210°C; 2,16kg	D1238
Relative viscosity	1	g/10min	T=210°C; 2,16kg	D1238
Color			Transparent	
Melting Temperature	145-160	°C		D3418
Glass Transition Temperature	55-60	°C		D3418
Ultimate Strenght	60	MPa		D882
Young Modulus	3,6	MPa		D882

The strand densities were measured using the Gibertini Eternity Balance, which employs Archimedes' principle by comparing the weight in air and in water. Foamed strands were examined using a Hitachi High-Technologies Corporation TM3000 electronic microscope (SEM) to investigate the micromorphology of the foam. The specimens were prepared by cutting and flash-freezing with liquid nitrogen using an Astra Platinum blade. Metallization of the specimens was achieved using a K650X Sputter Coater from Quarum Technologies with gold as the filler material for surface conductivity. The mechanical behavior of each foamed strand was analyzed using micro-tensile tests conducted with a Deben Microtest 200N instrument. Custom jaws were designed and fabricated to securely grip the strand with epoxy resin during testing. In Figure 3, it is possible to see 3 cross section images made by scanning electron microscope of the strands realized at different extruder temperatures keeping constant the others process parameters. It can be noticed how, as the temperature increases, the bubbles tend to coalescence and escape as gas from the polymer. The strand realized with the lowest temperature has a final diameter of 2.6 mm and the one realized with the highest temperature has a diameter of 1.2mm. This put in evidence the need to accurately control the temperature during the printing to obtain a product with the desired microstructure.

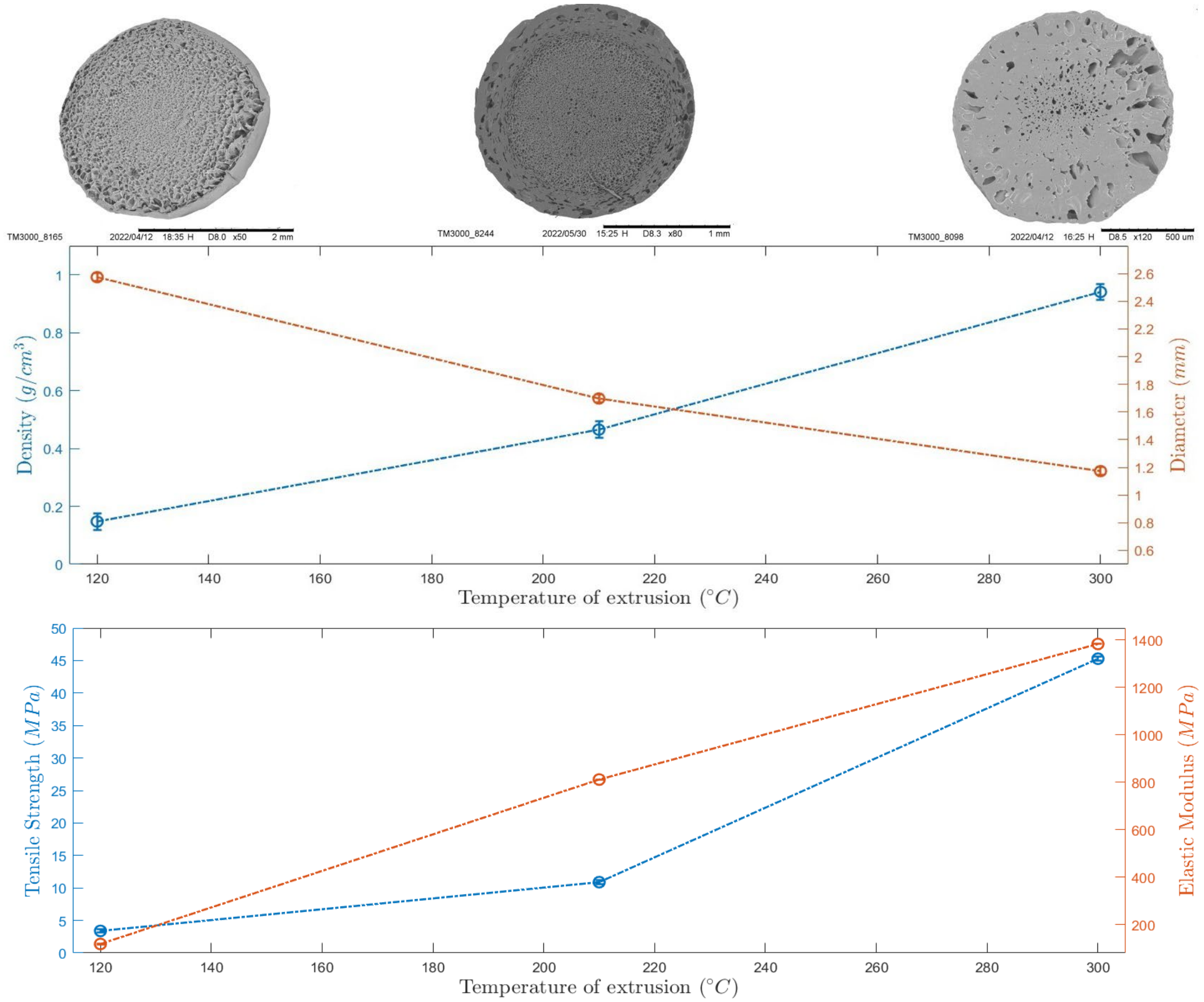


Figure 3 Influence of the temperature on the foam properties. P_a=32.5bar; T_a=33h; T_d=138h; N_d=0.7mm; S_e=675mm/min

The final density and diameter of the foamed strand strictly depends on bubbles size and location, as reported in figure 3. In the same figure, tensile strength and elastic modulus of foamed filaments are reported versus extrusion temperature. To establish the degree of robustness of the process and obtain a response surface methodology, we conducted a design of experiment with replication of the tests at the central point. While we will not report all of the test replications in this paper, it is important to note that our work with the response surface methodology is being published separately in another paper, which will be authored by [Lepore et al.]

By doing a screening of foam production of various thermoplastic polymers, the feasibility of the process could be verified with a series of tests as example the properties and morphologies obtained for various polymers are shown in the following figure.

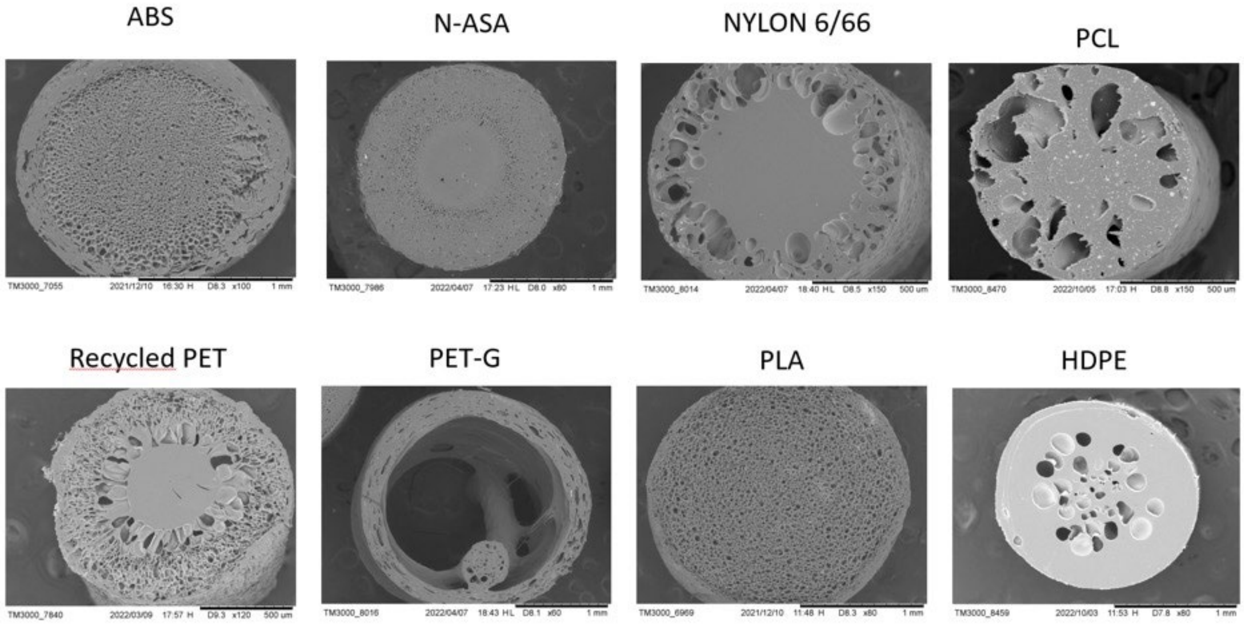


Figure 4 Different thermoplastic polymers foamed with FAM technology

Conclusions

In conclusion, this paper presented FAM as a novel method for 3D printing of foams. FAM has the distinct advantage of producing gradient foams with the highest level of free-form design allowed by additive manufacturing.

- FAM allows for the creation of complex structures with intricate internal geometries that would be difficult or impossible to achieve with traditional manufacturing methods.
- Precise control over printing parameters is necessary to produce high-quality objects with FAM. This includes the extrusion temperature, pressure, speed, and die geometry, which can significantly affect the expansion of the polymer and the resulting foam morphology.
- Future research in FAM should focus on further improving control over the printing parameters and developing new materials and printing techniques to expand the range of possible foam structures and properties.

Overall, FAM is a promising avenue for the production of foams with tailored structures and properties and has the potential to revolutionize the field of foam manufacturing.

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