Analytical Model of Fused Thermoplastic Extrusion

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Introduction to Pellet Additive Manufacturing

Motivation of the research

- Industry 4.0 has introduced new business models focused on consumers and product customization. As a natural consequence, both the quantity of the service provided and the added value have increased.

- Additive manufacturing (AM) plays a key role in the Industry 4.0 scenario, leading to the manufacturing of a physical three-dimensional object starting from a computer-aided design (CAD) model.

- AM satisfies the growing need for product customization, leading to the development of functional, flexible, and efficient parts and assemblies.

- Moreover, AM allows substantial savings in terms of logistic costs, giving the opportunity to perform 3D printing once the printing file has been acquired, wherever the 3D printer is located. Then the CAD file, it is converted in a series of slices through a slicing software (e.g.: Cura, Slic3r, Simlify3D, PrusaSlicer). Finally, the slices are transformed in a prescribed series of movements to be followed by the extrusion system, written in G-Code. The manufacturing process starts when the extruder starts to follow the instructions written in the G-Code file, manufacturing the final part layer-by-layer.

Overview of Fused Filament Fabrication

Fused Filament Fabrication (**FFF**) is an AM process which consists in manufacturing products starting by extruding a polymeric material given in the form of a filament, which is then gradually molten through an extrusion system.
Initially, the thermoplastic material is wound onto coils (*build material spool* in **Fig.1**).

It is pushed down by a pair of drive wheels, set in the extrusion head.

Then, the filament reaches the heated part of the extrusion system, namely the **liquefier**.

A gradual **melting** process begins because of the heat generated by a series of resistors.

Finally, the fused filament is **extruded** through one or more nozzle/s and it is deposited into a temperature-controlled environment, usually an oven.

The process continues through a **layer-by-layer** deposition until the final object has been built.

Because of possible overhangs in the final part, other materials can be used as supports and erased via mechanical/chemical methods (*support material spool* in **Fig.1**).

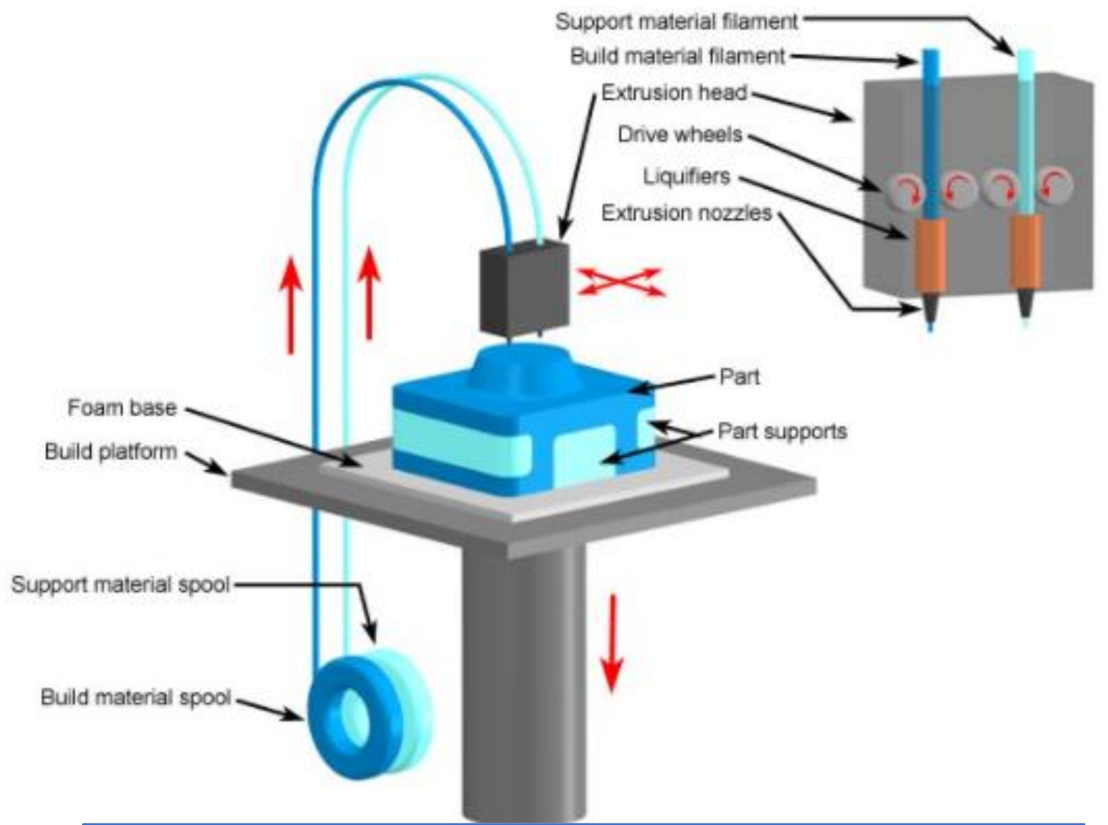

Fig.1: FFF overview (Dhal 2018)

Overview of Pellet Additive Manufacturing

Recent developments in AM have moved towards a new trend in material extrusion processes (ISO/ASTM 52910:2018), dealing with the direct extrusion of thermoplastic and composite material from **pelletized** feedstock (**Fig.2**).

This growing interest is driven by the reduction of costs, environmental impact, energy consumption, and the possibility to increase the range of printable materials.

Pellet additive manufacturing (**PAM**) can cover the same applications as FFF and, in addition, can lead to scale towards larger workspaces that cannot be covered by FFF, due to the limited diameters of standard filaments.

In the first case, the process is known as micro- or mini-extrusion (**MiE**) in the literature, in the second case the expression big area additive manufacturing (**BAAM**) is very common.

Several models are available in literature regarding FFF, while there is a lack of modeling of the extrusion dynamics in PAM; this is the **motivation** for the research: to create a first code aiming at describing the PAM extrusion process.

Fig.2: Concept art of a PAM extruder

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AM thermoplastic extrusion - Structure

In **Fig.3** the main structural differences between FFF and PAM have been shown. In a PAM extruder there is a single-screw extrusion system, placed vertically inside a heated barrel; screw root diameter varies along the extrusion axis, to provide the pressure needed for extrusion. The pellet feeding mechanism differs from that of the pushed filament of FFF; indeed, while in FFF there is a pair of wheels that push the filament inside the heated cartridge, in PAM the pellet is conveyed through two **combined** mechanisms:

- **gravity –** due to the vertical arrangement
- **Pressure build up –** due to screw shape

The inlet pressure (at: *pellet inlet* – **Fig.3b**) is the athmospheric one.
However, pressure increases in the first two screw zones (*solid-conveying* and *compression zone*); then, there is a pressure drop along the next ones (*metering zone* and *extrusion nozzle*).
The nozzle pressure outlet is different from inlet, because the **counterpressure** generated by the layer being deposited on the build plate must be accounted for.

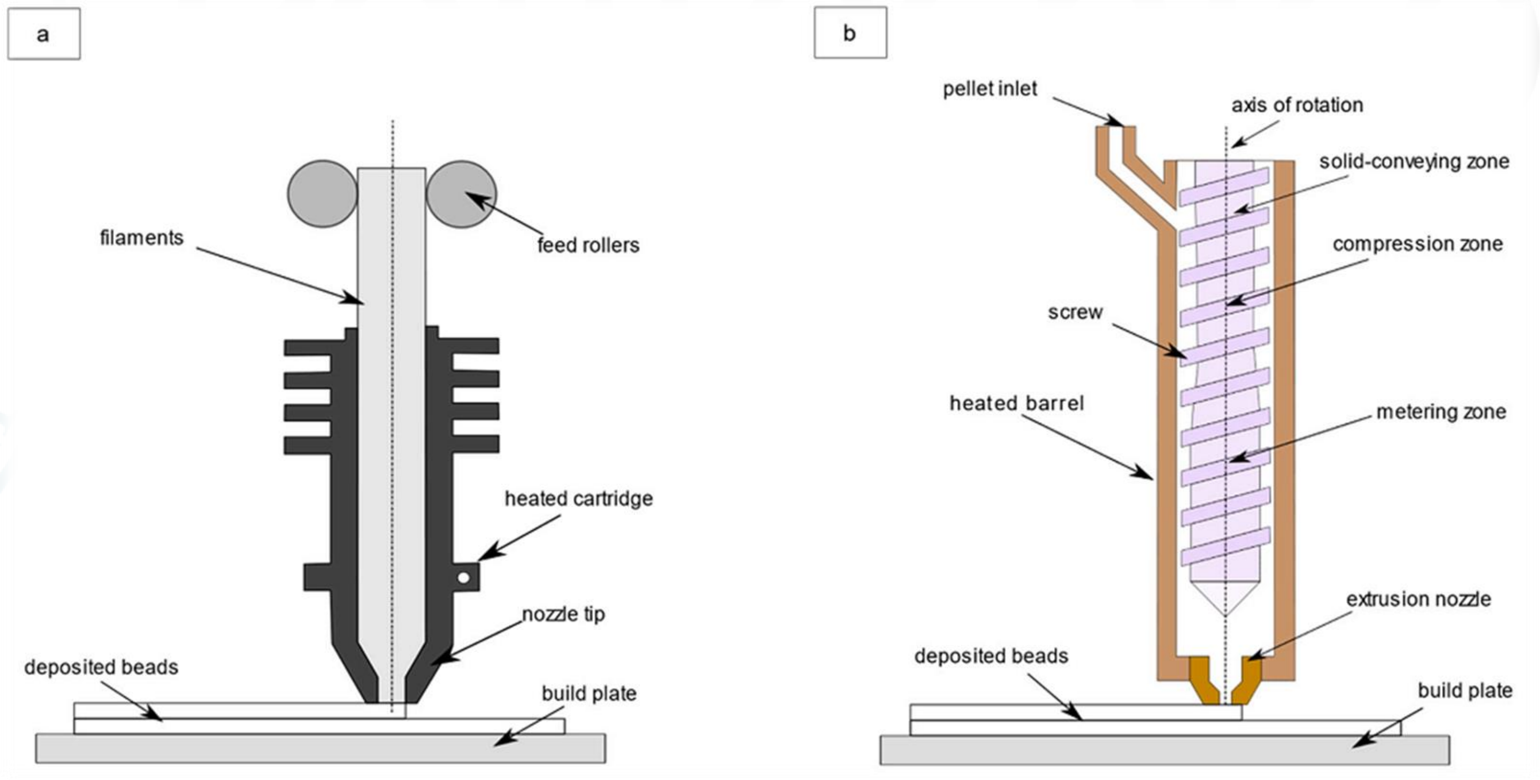

Fig.3: Schematic representation of: a.) FFF; b.) PAM extrusion processes

Advantages of Large Format 3D Printing

Some of the limitations that characterize FFF can be overcome by PAM extrusion:

Aspect	FFF	PAM
Material cost	High cost of the filament	Same material, given as pellet feedstock, costs up to 20x less
Printable material	Only commercial filaments	Unlimited
Energy consumption	High, for traditional FFF systems	No need for an heated oven, which saves up to 95% of energy (**Fig.4**)
Environmental impact	High	Simple disposal, for pelletized material
Printing volume	Up to 0.3[m^3]	Over 7[m^3]
Productivity	Limited, because the extruding nozzle diameter is usually less than 1[mm]	Up to 200x, with nozzles whose diameter is much higher (30x for BAAM-CI)

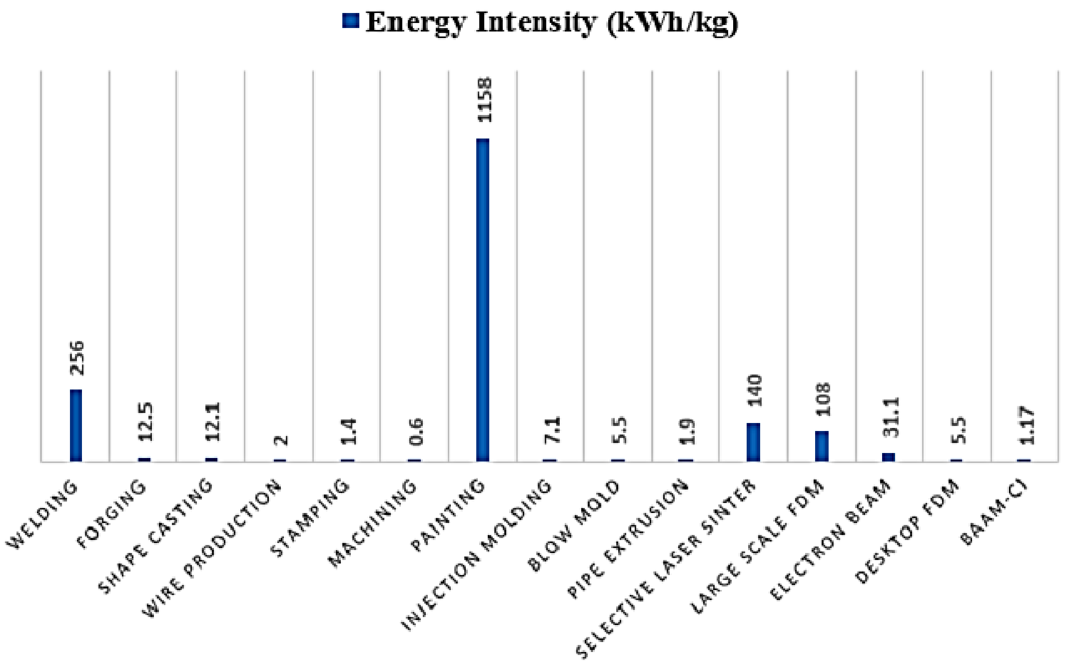

Fig.4: Energy consumption for the main manufacturing processes (Post, 2016)

An analytical code for Single-Screw Extrusion

Description of Single-Screw Extrusion

In recent literature there is no model aiming at describing the whole extrusion dynamics, from pellet inlet up to its deposition on the built plate; for that reason, two manufacturing processes which share a lot of common aspects with PAM extrusion have been analyzed, namely:

- Injection moulding (**IM**)
- Single-screw extrusion (**SSE**)

The internal architecture is very similar to a PAM extruder (**Fig.5**).

- The material is **conveyed** through an hopper in a screw-barrel system
- The **solid** material is handled by the screw
- When it arrives in barrel section heated above the polymer melting point, a **gradual melting process starts** near the **polymer-barrel interface**
- Melting proceed also **laterally**, in the vane between the pushing and trailing flight
- The material is subject to a gradual *compression* process, with an increase in pressure, because of the local screw geometry
- The molten material is then **metered** towards the die (SSE) or mould (IM); in last case, it is **injected** by means of a purely axial screw motion (IM), which is absent when dealing with SSE and PAM extrusion

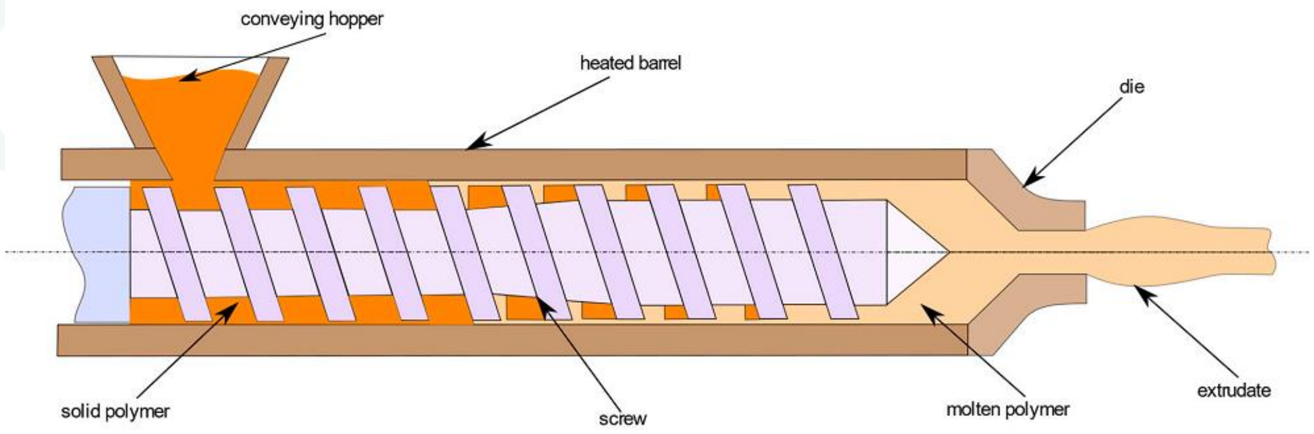

Fig.5: General metering-type screw for IM and SSE processes

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Review of codes for PAM description

The first step has been that to review the models for IM and SSE extrusion. The first aim of the work was to study the models used for thermoplastic material extusion with respect to the three main zones in which a PAM extruded can be divided (**Fig.6**). Another critical goal was to find what is the effect of the screw dimensions on some of the main aspects of the extrusion process, namely:

- **Melting length:** the portion, along the helical extrusion channel, where there is still a solid pellet residual
- Possibility to implement **reverse kinematics conditions**, namely to give the motion to the barrel instead of the screw
- Possiblity to neglect the **channel curvature**

All these assumptions allow for a **complete** semi-analytical modelling, for a given rheological model: the power-law. The material used in next investigations is **ABS MFI-22**.

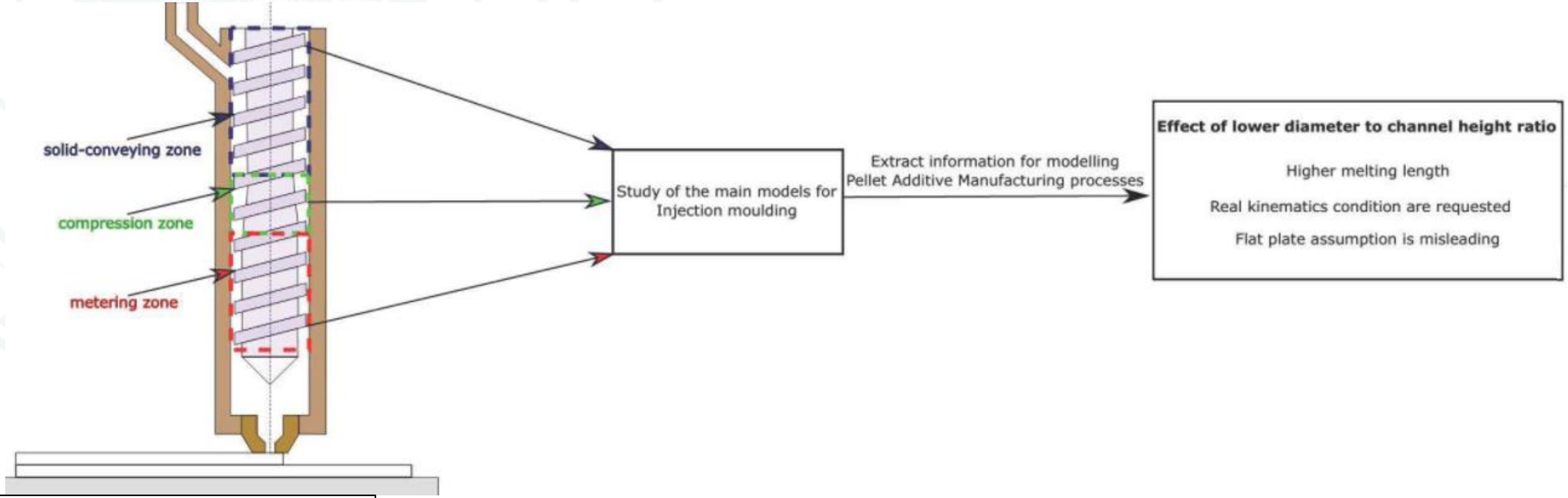

Fig.6: Information for PAM modelling, both at low (MiE) and high (BAAM) dimensions (Pricci 2022)

Extrusion of power-law fused thermoplastic materials

A **Matlab** code has been created with the purpose of describing all the phases of the extrusion process, in the case of **SSE**. After this first step, the model has been extended to deal with PAM extrusion.

The code has an iterative nature, and follows some steps:

- A trial mass flow rate is imposed
- The whole pressure profile is calculated, from inlet (*hopper*, **Fig.7**) to outlet (*extrusion nozzle*)
- The pressure at nozzle outlet must be the atmospheric one (zero relative pressure); pressure ratio (final to atmospheric) is calculated at each iteration and used as convergence check
- Mass flow rate is modified according to the abovementioned pressure ratio, and these fuor steps are repeated up to convergence

The assumptions for the model are the following:

- The discrete nature of pellet is neglected
- Melting according to Tadmor model
- Motion imposed to the barrel
- Power-law fluid $\mu = m_0 \dot{\gamma}^{n-1} e^{-a(T-T_0)}$
- Negligible channel curvature

The experimentation has been done on a *two-stage screw*, namely the **Noztek Pro** (**IAM Lab**, Polytechnic University of Bari).

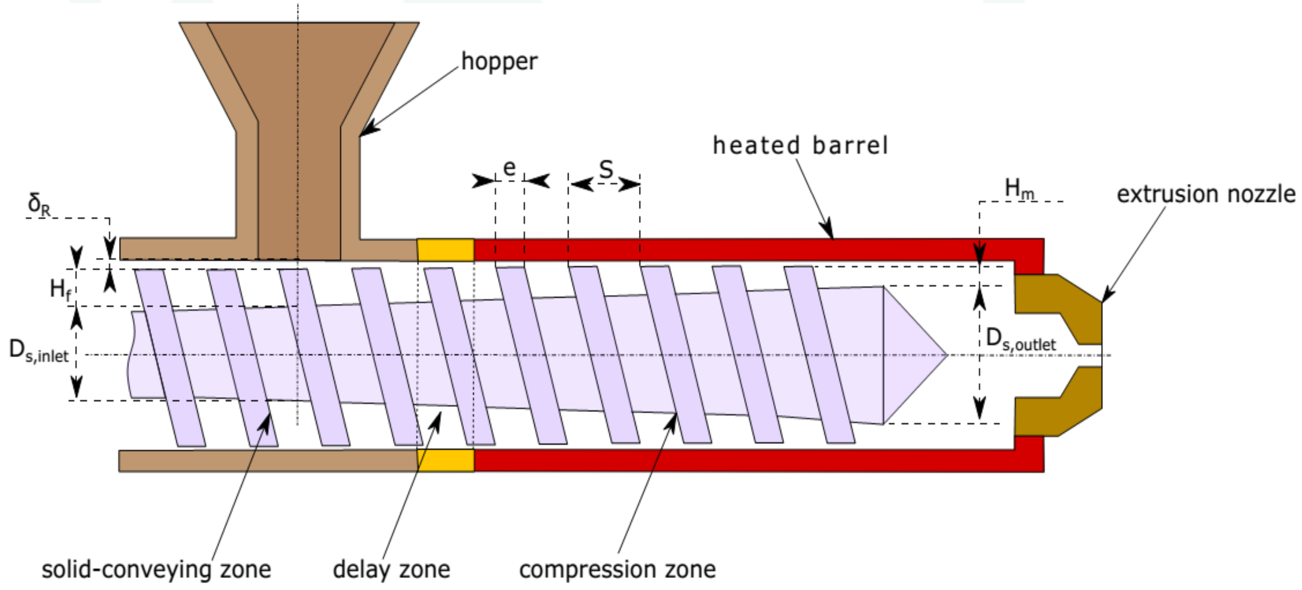

Fig.7: Details of the zones constituing the investigated two-stage SSE

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Experimental procedure

The main purpose of the validation process is to calculate the mass flow rate being extruded by the Noztek Pro. The following steps have been followed:

- The material is extruded freely through the heated nozzle
- The video recording of the entire extrusion process is started
- A marker is made on the extrudate, by means of an indelible pen
- The process is repeated, with the purpose to obtain other samples
- The screw is stopped and the whole extrudate is cut off
- The extrudate is further cut in the marked points, so to obtain the samples
- Samples are weighted with a Kern Emb 200-3 balance (resolution of 0.001 g; full scale of 200 g)
- The recorded video is post-processed through the video annotation tool Kinovea and the time interval between two successive marker positioning is evaluated
- Finally, the mass flow rate of a given sample is estimated as the ratio between its measured mass and the time interval

Mass Flow Rate Evaluation	
Mass flow rate (**experimental**; 7 samples):	0.250 ± 0.028 kg/h
Mass flow rate (**semi-analytical** code):	0.227 kg/h

An analytical code for PAM Extrusion

Semi-analytical code for PAM modelling

The same two-stage screw has been employed to study analytically the PAM extrusion process. A schematical representation of the internal features has been given in **Fig.8**.

The iterative process being formulated for the extrusion in free air (SSE) has been applied to the description of the PAM process, by accounting for the **counterpressure** generated by the **deposited layer**; this is characterized by a height t, always less than nozzle exit diameter D_{ext}. The relative pressure at nozzle exit is no longer zero because of the counterpressure generated by layer deposition.

There exist **two** new operating parameters:

- V_p – printing speed (given to plate – r.k.c.)
- t – layer height

The influence on the main process outocomes (mass flow rate and melting profile) must be evaluated.

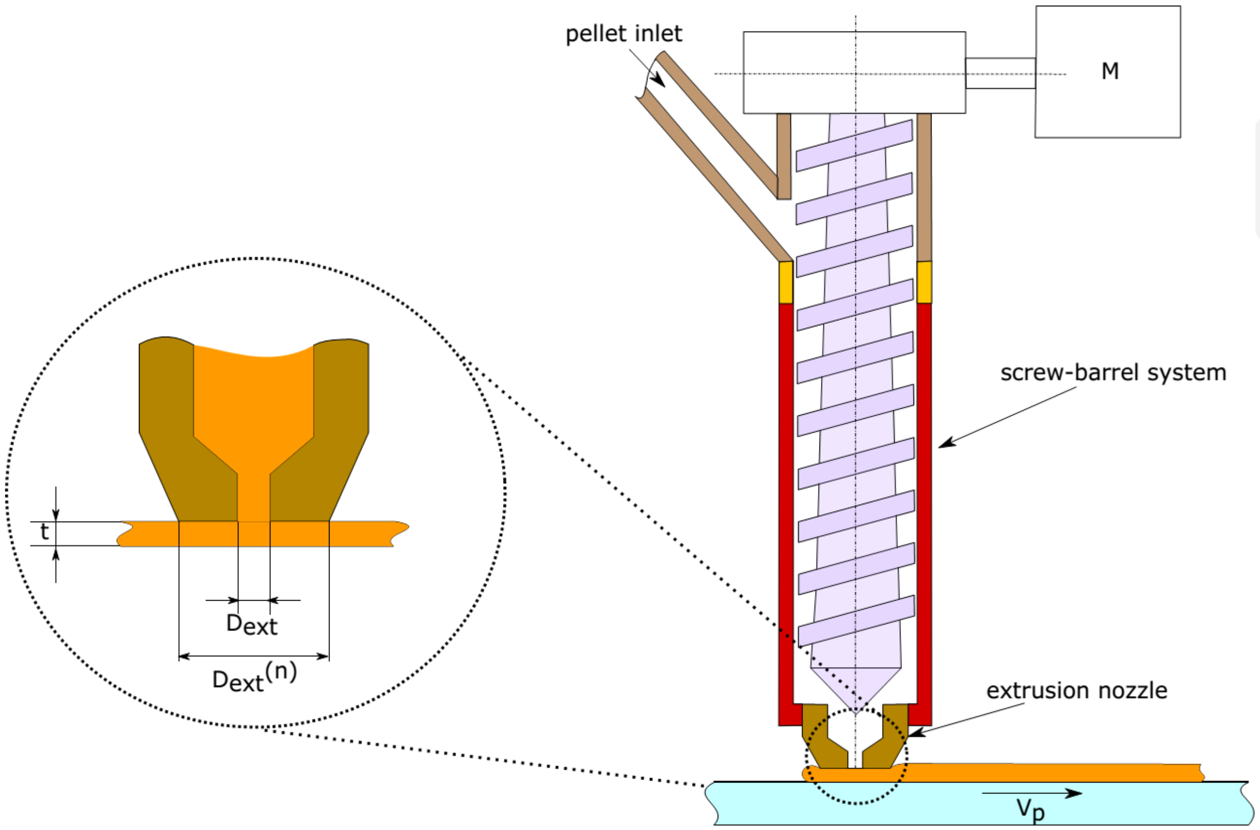

Fig.8: Scheme of PAM extrusion; D_{ext}: nozzle exit diameter; $D_{ext}^{(n)}$: nozzle external diameter; V_p: printing speed; t: layer height

PAM simulations

In the following table, the explored combinations for the two possible parameters have been reported (9 simulations, in total).

Layer height is always **less** than nozzle exit diameter (1.6[mm]).

Parameter name	Symbol	Value
Printing speed	V_p	1[mm/s]
		5[mm/s]
		10[mm/s]
Layer height	t	0.4[mm]
		0.8[mm]
		1.2[mm]

From IM literature, where there exist a counterpressure generated by the closed die (*mould*), it is well known that the maximum mass flow rate that can be extruded is always less than the one that could be extruded via SSE (zero counterpressure, in this case).

This is a required control on the maximum mass flow rate value which can be obtained through these simulations.

It is expected that a major counterpressure produces a reduction in mass flow rate, because the first quantity influences the entire pressure profile, upon which convergence of the mathematical model is based.

Moreover, from previous literature about FFF, counterpressure drops with increasing layer height and decreasing priting speed. For that reason, a mass flow rate increase is expected in both cases.

Results and Discussion

Mass flow rate evaluation

From **Fig. 9a** it is clear that the mass flow rate which the PAM extruded can dispose increases with layer height, for given printing speed.
This is also coherent with what is expected: lower layer heights, which bring also better printing resolutions, are associated with higher counterpressures, which decrease the mass flow rate that can be extruded.

From **Fig. 9b** it can be noted that mass flow rate decreases with printing speed, for a given layer height.
These trands are absolutely coherent with previous works on FFF modelling.
Finally, the check on the maximum mass flow rate gives good correspondence: the maximum value over all the simulations in 0.223[kg/h], lower than the value found in SSE application (0.227[kg/h]).

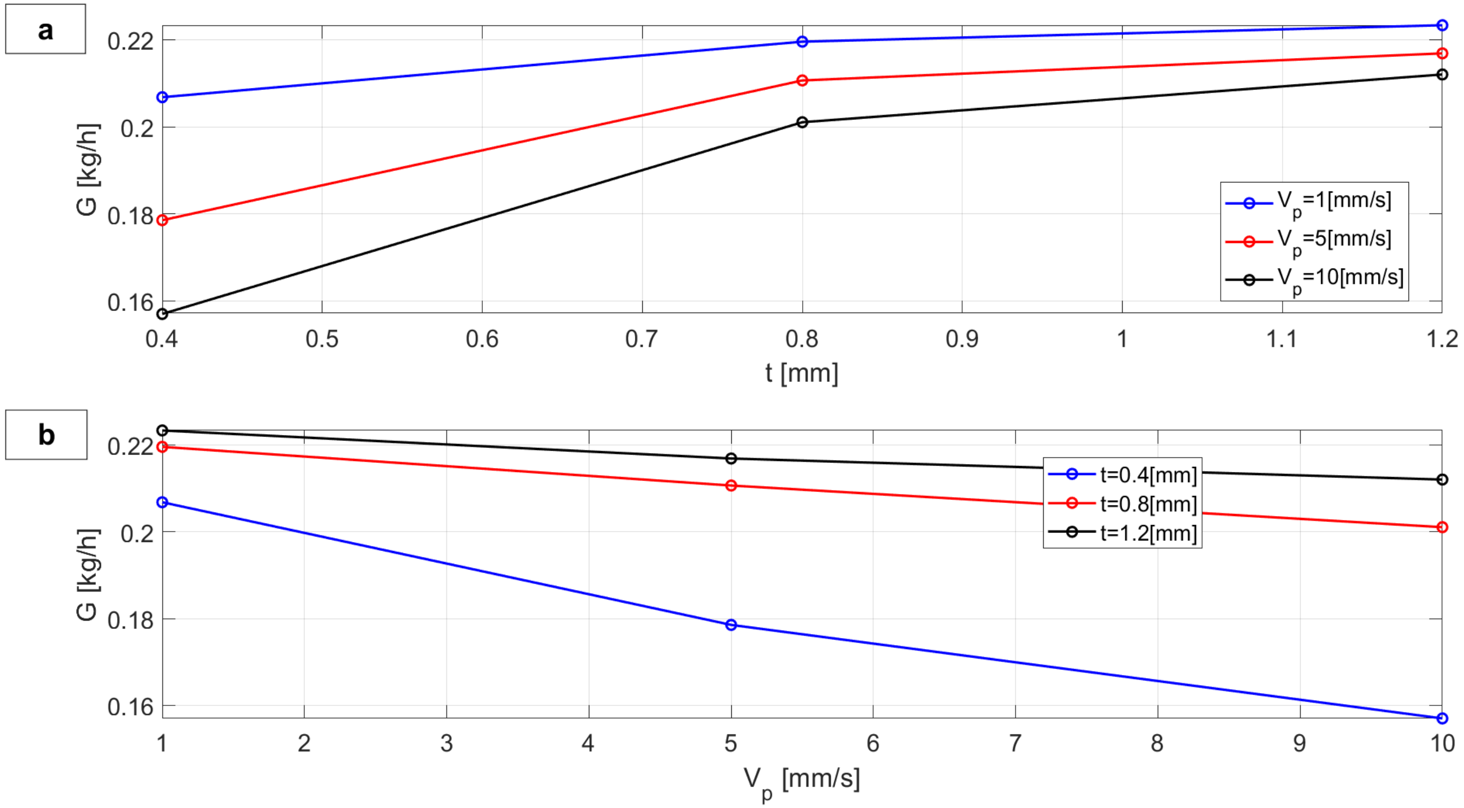

Fig.9: Extruded mass flow rate in PAM extrusion, for different printing speed and layer height

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Melting profile in PAM extrusion

In **Fig.10**, melting profiles at different printing speed have been reported:

- V_p =1[mm/s] (a)
- V_p =5[mm/s] (b)
- V_p =10[mm/s] (c)

In this case, it can be observed that by incresing the layer height it follows a spatial melting delay.

This effect results almost undetectable at low printing speed (a), while at the higher ones (c) it is remarkable, especially for the lower layer heights.

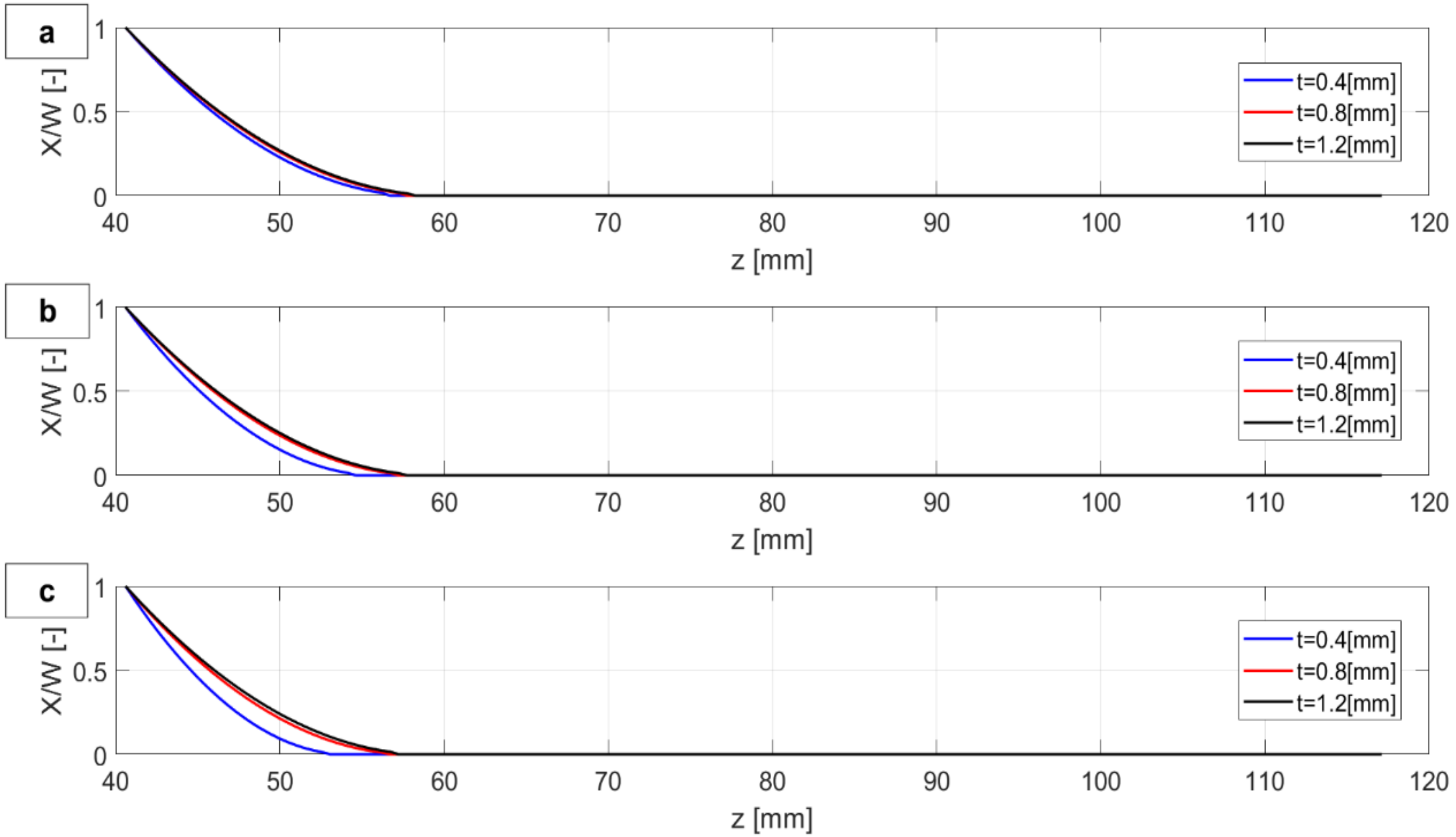

Fig.10 : Melting profiles in PAM extrusion

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Mass flow rate results at different screw speeds

Finally, the results have been analyzed at different screw speed (**Fig.11**).
The trends are the same as already noted for the reference screw speed (N=39.55[rpm], in *Fig.11*).
The same conclusions have been documented also for melting profiles.

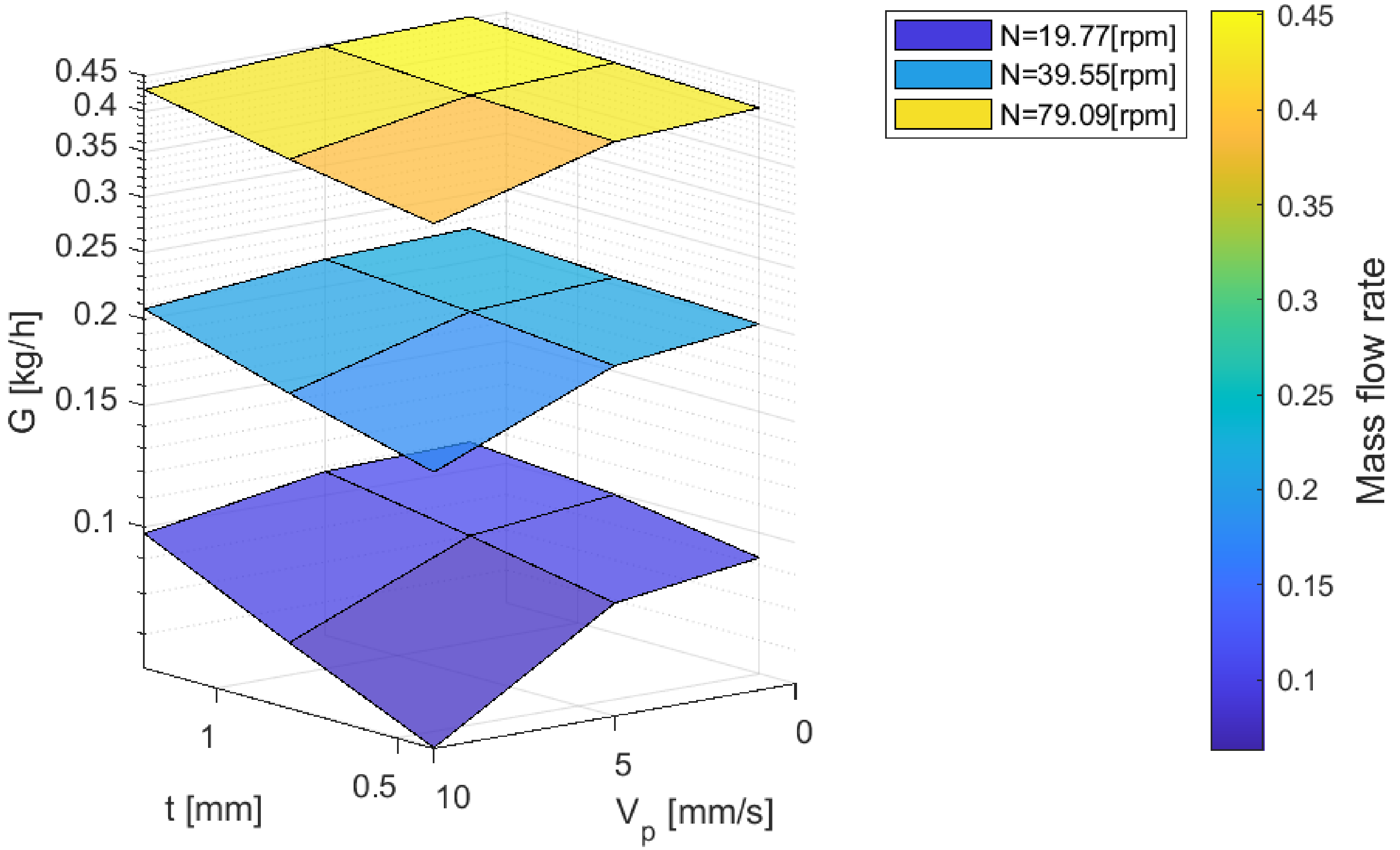

Fig.11: Extruded mass flow rate in PAM extrusion, at different screw speeds

Future works

Future Works

Commercial thermoplastic materials' rheology is better fitted by a Cross-WLF model (e.g.: LATILON thermoplastic, **Fig. 12**).

Three main behaviours can be distinguished:

- **Newtonian regime**: dynamic viscosity does not depends on shear rate
- **Transition zone**: at intermediate shear rates
- **Power-law zone**: in a double logharitmic chart, dynamic viscosity decreases linearly with shear rate; here the semi-analytical model applies

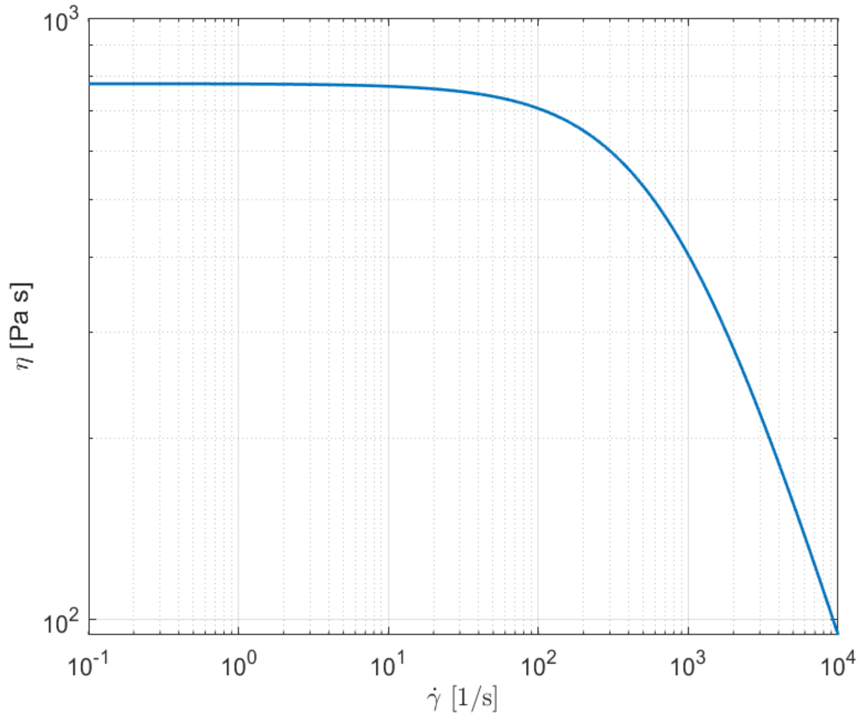

Fig. 12: LATILON rheology (Lati s.r.l. data)

The main advantage of Cross-WLF is in the accurate description of polymers' rheology both at high and low shear rates.

In particular, for BAAM applications, where nozzles diameters are up to 1[cm], shear rates are very low, and thermoplastic mostly behaves as a Newtonian fluid (at least, inside the nozzle).

For that reason, the code needs to be extended, with respect to the fluid dynamics inside both screw and nozzle.

Another point will be that to extend the experiments to deal with more compex PAM extruders (i.e.: other screw types).

Publications

International Journals

Pricci, A.; de Tullio, M.D.; Percoco, G. Analytical and Numerical Models of Thermoplastics: A Review Aimed to Pellet Extrusion-Based Additive Manufacturing. *Polymers* **2021**, *13*, 3160. https://doi.org/10.3390/polym13183160

Pricci, A.; de Tullio, M.D.; Percoco, G. Modelling extrusion-based Additive Manufacturing from pelletized thermoplastics: analytical relationship between process parameters and extrusion outcomes. **Submitted to Journal**

Pricci, A.; de Tullio, M.D.; Percoco, G. Semi-Analytical Models for Non-Newtonian Fluids in Tapered and Cylindrical Ducts. **Submitted to Journal**

Thanks for your attention

Q&A