Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Insights on Multi-Extrusion Filament Fabrication: Exploring the Impact of Seam Overlap and Ironing Process

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Abstract

Within additive manufacturing technologies, polymer extrusion has witnessed significant development in recent years. Nonetheless, the manufacturing of large-format parts remains a challenging task. Cooperative and independent extrusion systems show promise for the efficient fabrication of large components, but often introduce problems such as seams (bonding between material deposited by different extruders) that act as localized part weaknesses. Given that the diffusion of polymer molecules through a given interface depends on the available contact area and is greatly influenced by temperature, the authors hypothesize that increasing the contact surface and local temperature might improve part strength. In this study, the authors evaluate how overlapping seam areas affect the tensile properties of PLA samples produced with multiple extrusion systems. Besides overlapping, the effect of ironing (a thermal-based post-processing technique originally designed to smooth the top layers of parts) in overlapped areas is also studied. Results highlight the importance of overlaps and confirm that the fracture mechanism of heat-affected areas is different when compared with non-affected ones, suggesting that the mechanical properties of parts with seams can be improved, but further studies are needed. With this knowledge, the authors aim to help the process of designing large polymer parts using collaborative 3D printing.

Keywords: Joint, FFF, Large-format.

Introduction

Additive manufacturing (AM) refers to a group of processing technologies where material is sequentially deposited or consolidated, usually in a layer-by-layer manner. In contrast to conventional manufacturing, AM technologies offer unparalleled design freedom, making it possible to create components with tailored properties while potentially minimizing waste and production costs [1]. Within AM process families, material extrusion-based technologies perform a controlled deposition of materials, followed by solidification through heat dissipation, chemical reactions, or solvent evaporation. Fused filament fabrication (FFF) is the most widely used extrusion-based technology in which solid polymer filaments are heated and extruded through a nozzle onto the build platform [2].

It is commonly recognized that one of the benefits of FFF technologies is their ability to avoid extensive design for manufacturing requirements [3]. Even so, several design practices can help improve aspects such as production time, cost, and the manufacturability of parts. Advantages such as the practicality and affordability of FFF have contributed to its widespread adoption, but the production of large-format polymer components remains a challenging task due to limitations in speed, cost, and the scalability of parts [4], [5].

A common practice to obtain large FFF parts is to join multiple smaller parts, independently produced. The review by Tiwary et al. [6] analyzes joining techniques for FFF parts, including welding, adhesives, mechanical interlocking, and the use of fasteners. Alternatively, to avoid joining-related issues, solutions based on independent extrusion modules that collaborate to simultaneously produce a part have emerged [7], [8], [9]. Such solutions aim to allow cost- and time-efficient production of large parts while ensuring the geometric precision of smaller systems [10]. Naturally, the integration and collaboration of multiple extrusion systems increases the complexity of production and usually results in intersection areas within the parts, also treated as seams or joints [11], [12], [13]. Therefore, understanding the mechanical properties of these seams is crucial for the design of large-format polymer parts. Examples of parts with seams fabricated by multi-extrusion filament fabrication (MEFF) are shown in Figure 1.

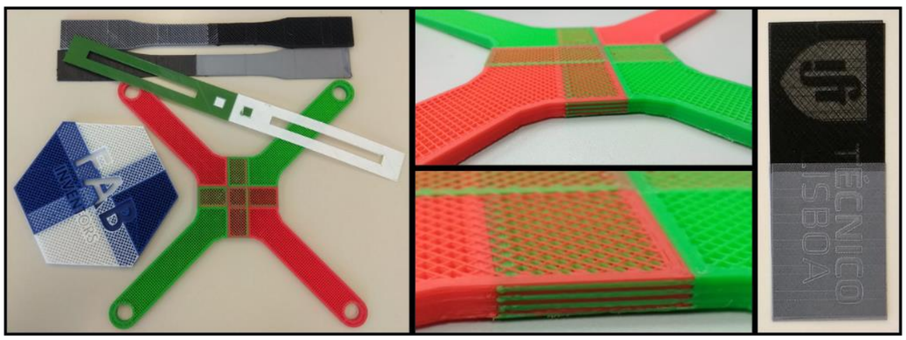


Figure 1: Parts produced with MEFF that exemplify different types of seams.

Improving and predicting the mechanical properties of FFF parts is fundamental for designers who wish to optimize the weight and strength of their parts [14]. Regarding MEFF, Zhang et al. [15] developed a data-driven predictive model that allows designers to assess the tensile strength of components fabricated by cooperative 3D printing. Most FFF design rules still apply when designing large components, but factors such as build orientation, material throughput capabilities, and infill strategies are especially relevant in large-sized products [16]. In MEFF, these factors can also affect seam location and the allocation of part sections to individual extrusion modules.

With this study, the authors aim to provide guidance for the design of sizable polymer components through collaborative FFF techniques. In previous research, the authors took advantage of a dedicated manufacturing apparatus [17] and slicer software [18] to evaluate the influence of simple seams on the mechanical properties of polylactic acid (PLA) samples produced with two independent extrusion modules. The experiments revealed that the seams introduce a localized fragility resulting in a general reduction in the mechanical strength of parts [19], which can be attributed to insufficient interdiffusion between adjacent polymer strands [20]. Given that the diffusion of polymer molecules through a given interface depends on the available contact area and is greatly influenced by temperature, one could hypothesize that increasing the contact surface and local temperature might mitigate the issue. Ironing, a thermal scanning post-processing technique initially developed to smooth the top layers of parts, remains largely unexplored for its potential in enhancing properties beyond superficial smoothness.

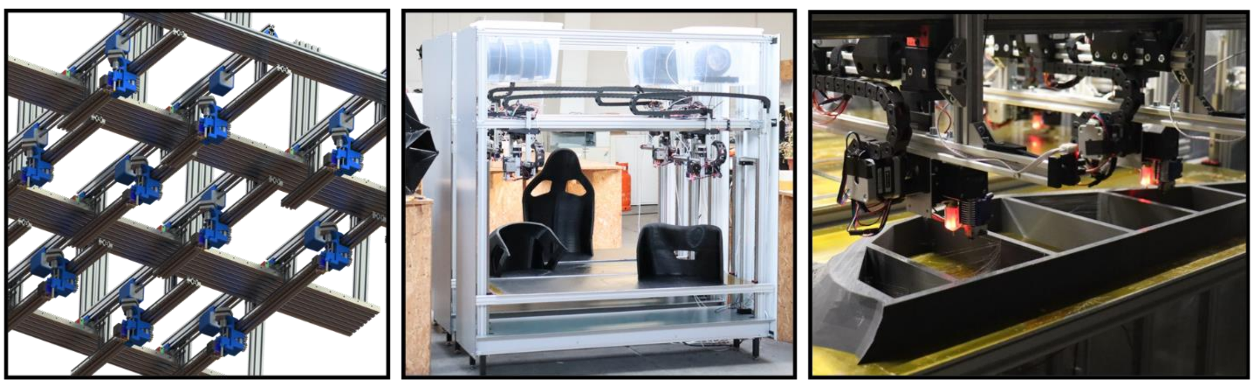
In this work, the authors investigate the influence of seam overlap and ironing on the strength of PLA tensile specimens produced with two independent extrusion modules. To do so, test specimens were fabricated, varying the seam overlap area, the amount of extruded material during ironing, and the relative orientation between ironing and deposition paths.

Materials and methods

ASTM D638 type I test specimens were produced using an FFF machine with two independent extrusion modules with a 0.1 mm layer height and 0.4 extrusion nozzles. The material chosen for the study is PLA, a biomass-derived thermoplastic used in numerous fields of application. When processed by FFF, its reported tensile strength can vary between 10 and 60 MPa depending on process parameters, namely build orientation, layer height and extrusion temperature [21], [22]. After production, the samples were consecutively tested using a universal testing machine Instron 5566 with a 10 kN load cell and a crosshead speed of 2 mm/min. The following sections provide further information about the MEFF apparatus, the seam location, the overlap extension, and the ironing process.

Multi-extrusion and collaborative fabrication

The MEFF machine used in the study has multiple independent extrusion modules capable of collaborative manufacturing, as seen in the render of the extrusion modules of Figure 2a. Figure 2b shows the MEFF machine used to produce the specimens. The machine uses a dedicated slicing software based on a concept first proposed by Frutuoso [18], which enables cooperative production using collision-avoiding strategies. Two extrusion modules collaborated in the production of each specimen. The collaborative process of producing a large FFF part is exemplified in Figure 2c.



(a) (b) (c)

Figure 2: a) CAD rendering of a modular MEFF machine featuring multiple extrusion modules; b) Actual MEFF machine used for specimen production; c) Representative ilustration of the MEFF machine producing a large FFF component.

Seam location and overlap

The specimens were designed with two distinct regions separated at the centerline. In this case, these are samples with a [0; 0] seam overlap, in which the slicing parameters are adjusted to ensure that each extrusion head deposited material only up to the specimen's centerline. In the samples featuring a [-10; 10] seam overlap, material deposition was extended by 10 mm away from the centerline, with alternating directions for each layer, i.e., a total of 20 mm of alternated overlapped length between layers. The deposition toolpaths were programmed to create two contour layers around the part's perimeter, excluding the seam interface line. These were then followed by linear infill, alternating the raster angle between 45° and -45° in each layer. A representative specimen with a [-10; 10] seam overlap is shown in the scheme of Figure 3.

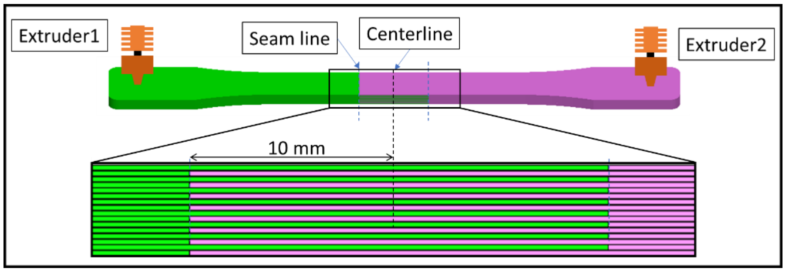


Figure 3: Schematic representation of a tensile specimen with a [-10; 10] seam overlap. Different colors representing different extrusion modules used.

Ironing in fused filament fabrication

Ironing is a post-processing technique originally designed to smooth the top layers of FFF parts that has seen recent developments and usage in the most common slicer software. As illustrated in Figure 4, the ironing process involves the heated nozzle scanning over a printed layer at a specified distance, with minimal to no material extrusion and typically employing a finer line spacing, resulting in smoother surfaces [23], [24]. Recently, Neuhaus et al. [25] examined various FFF filament materials, investigating the effects of ironing parameters such as speed, flow, line spacing, and temperature.

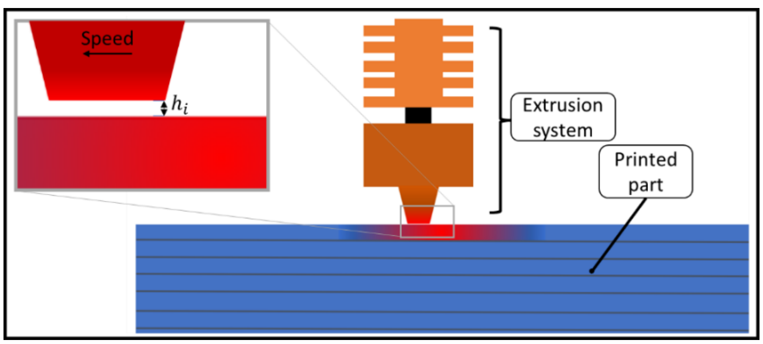


Figure 4: Scheme of the top layer of a FFF part being ironed [24].

Sardinha et al. [26] showed that ironing not only reduces surface roughness but also helps to minimize distortions in parts. Furthermore, even if this process might be advantageous over post-processing methods, it increases printing time, material usage, and energy consumption. Depending on process parameters such as ironing distance (hi), it has also been successfully used to promote the fusing of layers and fill gaps that may be present within them [27]. Notably, Griffiths et al. [28] performed ironing on a non-planar surface using a 5-axis FFF machine.

Experimental plan and nomenclature

Initially, a batch of control (C) specimens without seams was produced using a single extrusion head. For comparison, seamless specimens subjected to ironing parallel and orthogonal to the raster angle (PI0 and OI0, respectively) were also printed. In these cases, the ironing process was applied over the entire surface of each deposited layer, with no additional material flow involved. Specimens with [0; 0] and [-10; 10] seam overlaps (S0 and S10, respectively) were also printed to compare with the control samples. Furthermore, a 2^3 design of experiments (DoE) was employed to create ironed specimens with variations in seam overlap, material flow during the ironing process, and ironing direction. In these instances, ironing was applied in the vicinity of the seam location within each layer, extending by -1 mm and 1 mm in relation to the seam area. Table 1 provides a summary of the designations used for the various treatments. Three samples were fabricated for each treatment.

Table 1: Experimental conditions and corresponding nomenclature.

ID	Seam Overlap (mm)	Ironing Extent (mm)	Ironing flow (%)	Ironing Direction
C	None	None	-	-
PI0		Everywhere	0	Parallel
OI0				Orthogonal
S0	[0; 0]	None	-	-
S10	[-10; 10]			
S0/PI0	[0; 0]	[-1;1]	0	Parallel
S0/OI0				Orthogonal
S0/PI5			5	Parallel
S0/OI5				Orthogonal
S10/PI0	[-10; 10]	[-1;1]	0	Parallel
S10/OI0				Orthogonal
S10/PI5			5	Parallel
S10/OI5				Orthogonal

Results and discussion

The fractured specimens are presented in Figure 5. As expected for PLA, the specimens exhibited almost no plastic deformation. In the samples produced with a single print head (C, PI0, and OI0), the fracture occurs at a 45-degree angle, aligning with the infill deposition angle. In contrast, the specimens with a simple non-overlapping seam (S0) exhibit a clean fracture surface prependicular to the load direction, primarily located at the interface between the two independently produced regions. The same trend was observed in specimens with a simple non-overlapping seam subject to ironing in the vicinity of the seam (S0/PI0, S0/OI0, S0/PI5, and S0/OI5), regardless of the ironing parameters.

With respect to the samples containing an overlapping seam without ironing (S10), the fractures predominantly followed the infill pattern. The same observation applies to the orthogonally ironed specimens (S10/OI0 and S10/OI5), regardless of the ironing flow amount. Among the paralleled ironed samples (S10/PI0 and S10/PI5), two out of three from each treatment failed at the interface, despite the ironing flow amount. Besides indicating that increasing the available area for polymer diffusion through overlapping seams was more effective, the analysis of the fracture location suggests that ironing a seam region orthogonal to raster angle of the infill could promote joint strength.

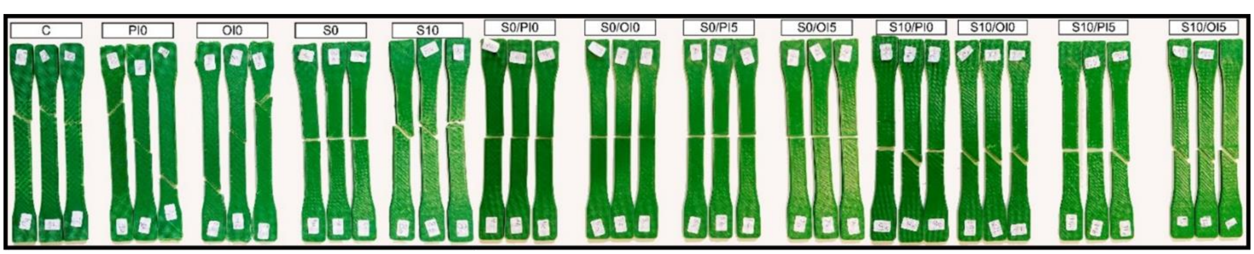
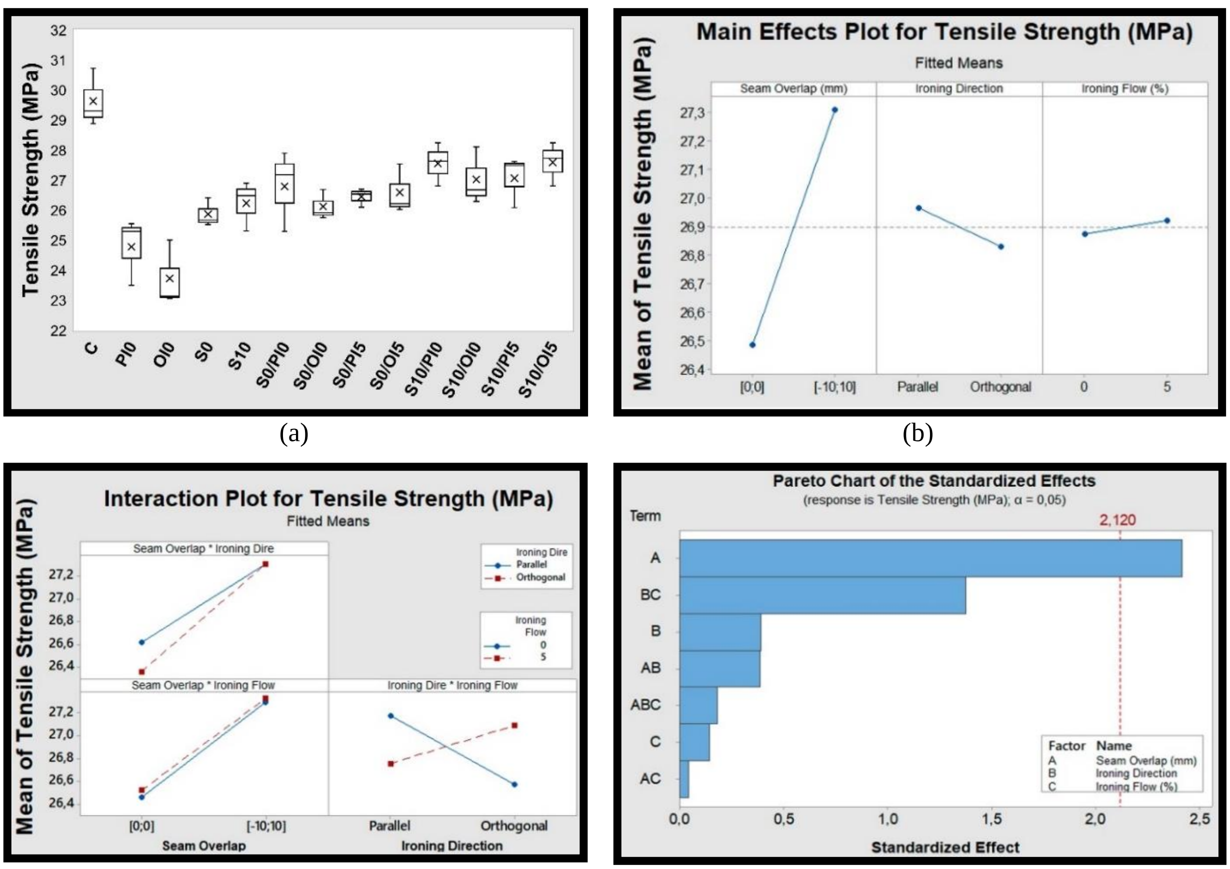


Figure 5: PLA specimens after tensile tests were performed.

Figure 6a shows a box plot chart with the variations in tensile strength according to the experimental treatment. The factorial DoE was further analyzed using Minitab® software, as shown in Figures 6b to 6d.

Confirming previous findings, a notable decrease in maximum tensile strength is evident across treatments in comparison to the control samples (29.63 ± 0.79 MPa). Apart from the evident weakening effect of the seams, a significant reduction in the mechanical resistance of the seamless specimens subjected to parallel and orthogonal ironing in every layer (PI0 and OI0) was noticed (24.78 ± 0.91 MPa and 23.73 ± 0.90 MPa, respectively). Since the ironing process subjects the material to additional thermal cycles, this might affect the crystallization of the material, or lead to polymer degradation. With relation to the specimens with seam and without ironing, the overlapping design resulted in slightly higher strength (26.23 ± 0.67 MPa) compared to the non-overlapping seam design (25.87 ± 0.39 MPa).

The specimens with seams that were subjected to ironing presented slightly improved tensile strength, with the overlapping design resulting in the highest values (around 27.5 MPa) compared to the non-overlapping design (around 26.5 MPa), regardless of the ironing direction and material flow. The values, however, fall in the same range considering the standard deviation.



(a) (b) (c) (d)

Figure 6: a) Box plot of strength variation across different experimental treatments; b) Impact of individual processing parameter on tensile strength; c) Combined effect of the influence of parameters on tensile strength; d) Pareto chart of the standardized effects on the tensile strength of the specimens.

Figure 6b shows the main effects plots, indicating a significantly positive influence of the seam overlap extent on the tensile strength of the PLA specimens. In fact, this is the only effect that can be clearly considered statistically significant, as seen in Figure 6d. This behavior indicates that the larger surface area created by layer overlap increased the likelihood of molecular interdiffusion between the adjacent strands deposited by each extrusion head. The main effects plot also shows that changing the ironing direction from parallel to orthogonal might have slightly reduced the tensile strength of specimens. Even so, applying parallel ironing frequently resulted in a clean fracture at the interface. Figure 6b also shows that using a 5% material flow during the ironing process might have a small positive effect, but further studies need to be done.

The interaction plot shown in Figure 6c indicates that ironing the seam vicinity orthogonally to the infill pattern (OI treatments) is more effective in improving the mechanical strength of the specimens with overlapping seams, regardless of the amount of extruded material during ironing. In contrast, the ironing direction and material flow presented an antagonistic interaction. However, as shown in Figure 6d, these effects cannot be considered significant at a 95% confidence level. Additional experiments are required to further characterize these trends.

Lastly, when using strain-gauges during the tensile tests, it was possible to observe that the deformation behavior between ironed and non-ironed areas of the same specimen varied. The measured strain in ironed locations was smaller than the strain measured in non-ironed locations.

Insights on design for multi-extrusion fabrication

As discussed in the work by Ali et al. [29], poor bonding between different extruded materials is one important aspect to tackle in the design of large-format multi-extrusion parts. The results of the present work emphasize the critical role of bonding quality in MEFF. Even when using a single material, the presence of a seam between segments created by collaborative modules weakens the part.

While increasing the contact area with an overlapping seam proved effective in enhancing the mechanical strength of tensile specimens, the thermal activation induced by the ironing process had a residual positive impact. In fact, given PLA's high susceptibility to thermal degradation as a biopolymer, any potential benefits of polymer re-melting for molecular interdiffusion may have been outweighed by property loss caused by molecular damage or an alteration in the crystallization of the material. Moreover, other ironing-related factors, such as the scanning speed, ironing temperature and nozzle height, might play a relevant role in achieving better results.

Given the influence of overlapping areas on seam strength, designers might need to avoid placing seams in specific locations, such as slender or latticed regions within parts. This underscores the importance of understanding efficient seam placement during production stages such as the slicing of MEFF components. Furthermore, considering that ironing or other thermal-based strategies applied to seams might increase production time and costs, it is important to minimize their usage.

Even so, to equip designers with the knowledge to confidently include seams in large-format parts produced by MEFF, further studies are needed. For this purpose, besides increasing the contact surface area, other joint designs capable of producing a mechanical interlock between the parts' segments have shown positive effects [30], [31].

Conclusion

The experiments performed in this research were aimed at providing guidance for the design and production of large-sized polymer components produced with MEFF. Following literature reports, results indicate that increasing the area for polymer diffusion through overlapping seams can improve the bonding quality of parts' sections printed with cooperative extrusion head modules and, thus, reduce the impact of the seams on the strength of specimens.

Regarding the application of ironing in the seam's location, ironed areas suffer a different deformation mechanism when compared with non-ironed areas of the same specimen. Furthermore, tensile testing and visual fracture analysis indicate that ironing the seam vicinity orthogonally to the infill may offer greater efficacy in enhancing specimen strength, as evidenced by smoother fracture surfaces. However, additional research that validates this hypothesis is needed, since this trend is not clearly displayed by an increase in tensile strength. Authors suggests that the reduction in the mechanical resistance of the specimens subjected to ironing over each layer might be related to polymer degradation or material crystallization. Since PLA is very prone to thermal degradation, the potential benefits of polymer re-melting for molecular interdiffusion may have been outweighed by property loss caused by molecular damage. Even so, from the tensile tests, it is possible to observe that ironed specimens tend to develop a plastic domain, suggesting that even if their tensile strength is not significantly improved, the extra thermal processing might be promoting some material diffusion. Additional experiments would be required to further characterize the impact of the thermal scanning of the seams.

Acknowledgements

This work was supported by Fundação para a Ciência e a Tecnologia (FCT), through IDMEC, under LAETA Base Funding (https://doi.org/10.54499/UIDP/50022/2020). This work has been also supported by the European Union under the Next Generation EU, through a grant of the Portuguese Republic's Recovery and Resilience Plan (PRR) Partnership Agreement, within the scope of the project PRODUTECH R3 – "Agenda Mobilizadora da Fileira das Tecnologias de Produção para a Reindustrialização", aiming the mobilization of the production technologies industry towards of the reindustrialization of the manufacturing industrial fabric (Project ref. nr. 60 - C645808870–00000067). Manuel Sardinha acknowledges FCT, for his PhD research grant, https://doi.org/10.54499/2021.04919.BD.

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