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# Exploring the Feasibility of Incremental Forming Applied to 3D Printed PEEK Sheets

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**Keywords:** single point incremental forming (SPIF), fused deposition modeling (FDM), polyether ether ketone (PEEK), manufacturing processes hybridization, polymer, biocompatibility.

**Abstract.** Incremental Sheet Forming (ISF) has been widely studied for metallic materials, demonstrating significant potential in flexible and low-cost sheet metal forming (aluminium, magnesium or titanium). Recently, attention has shifted toward polymeric materials due to their growing relevance in medical and customized applications (PCL, UHMWPE, PEEK). However, the availability of commercial sheets is limited to thicknesses, geometries, and material options. In this context, Fused Deposition Modeling (FDM) has emerged as a complementary technique to produce tailored polymeric sheets, enabling the integration of additive manufacturing with ISF processes to overcome limitations in available commercial sheets and expand design flexibility. Considering the success of this hybridization for forming PCL, this work investigates the feasibility of applying Single Point Incremental Forming (SPIF) to PEEK sheets produced via Fused Deposition Modeling (FDM). The study analyses the influence of printing parameters, forming conditions, and thermal treatment on part quality, porosity, forces, temperature, defects, and fracture behaviour.

## Introduction

Since the early developments of Incremental Sheet Forming (ISF), numerous research contributions have explored its suitability for manufacturing medical implants. Among the pioneering efforts, Ambrogio et al. [1] presented one of the first applications of Single Point Incremental Forming (SPIF) to produce a customized ankle support. The result demonstrated geometric deviations below 1 mm, highlighting the potential of SPIF for patient-specific components. Duflou et al. [2] were the first to explore the fabrication of a cranial prosthesis of AA3003-O aluminium using ISF, comparing it with hydroforming and significantly reducing the lead time (from 16.5 to less than 4 days). This approach was later extended to other body regions such as the maxillofacial area, denture/palate zones, and even orthopaedic sites like the clavicle, hip, and knee.

Although extensive research has been conducted on ISF applied to metallic materials, polymeric materials have also emerged as highly relevant in the medical field. In this regard, Fiorentino et al. [3] developed an innovative approach for the fabrication of plate prostheses using Incremental Sheet Forming (ISF) with Polycaprolactone (PCL), in combination with the Stereolithography (SLA) technique to produce molds or dies for the forming process. Later, Bagudanch et al. [4] confirmed the feasibility of ISF for manufacturing customized cranial implants made of UHMWPE, performing a comparative analysis between SPIF and TPIF processes. Likewise, Centeno et al. [5] produced similar cranial implants through SPIF using PVC and PC sheets. Yang et al. [6] proposed an experimental approach for thermally assisted SPIF of PEEK sheets (3 mm thickness), conducted at three different temperatures: 70, 100, and 150 °C. Later, Chen et al. [7] manufactured a PEEK cranial plate by thermal assisted SPIF showing its potentiality for medical applications. Rosa-Sainz, et al. [8]

presented an experimental investigation of Polyether ether ketone (PEEK) sheets deformed by SPIF at room temperature, determining the influence of the ISF process parameters on the material formability and revealing that the maximum strains achieved in two prosthesis geometries (cranial and cheekbone) remained well below the material's Fracture Forming Limit (FFL). However, the works dealing with PEEK and ISF are still scarce.

Overall, a broader application of SPIF to polymer sheets remains limited by the availability of commercial blanks, which offer restricted thicknesses and material type. Thus, having an alternative for producing customized blanks tailored to specific forming requirements becomes important. And in that sense, Fused Deposition Modeling (FDM) enables cost-effective fabrication of sheet-like structures with controlled geometry and composition, suitable for integration into SPIF processes. In this hybridization context, Rosa-Sainz, et al. [9] characterized the plastic formability and failure of PETG and PCL FDM and Garcia-Romeu et al. [10] proved its feasibility to deform them by ISF for the PCL sheets. In metal materials, Hasan and Akhtar [11] deposited material via AM on a preformed sheet that was subsequently formed, or Hafenecker et al. [12] and Ge et al. [13] analysed hybrid process chains that combined metal AM with forming processes and Ambrogio et al. [14] integrated Selective Laser Sintering and Single Point Incremental Forming to increase part complexity and functional performance.

This work investigates the feasibility of applying Single Point Incremental Forming (SPIF) to PEEK sheets manufactured via Fused Deposition Modeling (FDM). It will reveal how the printing parameters, the 3D printing machine and forming parameters can influence the forming results. Several sheets were manufactured using different printing strategies, with the aim of analysing their quality and porosity. Next, they were incrementally deformed using different SPIF process parameters with the aim of analyzing forces, temperature, defects, and breaks of the deformed parts. A comparison between sheets treated thermally and not is also presented, as well as the influence of using sheets printed with capabilities of different FDM machines.

## Methods

### Material and 3D FFF Printer Machine.

The material used was PEEK (Polyether Ether Ketone). PEEK is a high-performance, semi-crystalline thermoplastic polymer belonging to the polyaryletherketone (PAEK) family. It is known for its exceptional mechanical strength, thermal stability, and chemical resistance, which make it suitable for demanding engineering environments (aerospace, automotive or medical).

In this research two fused filament fabrication (FFF) printing machines were used with their corresponding PEEK supplier. Roboze Plus PRO FFF printer was used to print filament (Ø1.85 mm) supplied by ROBOZE and the process parameters were adjusted by means of Simplify3D software. Whereas Innovatefil® PEEK filament (Ø1.75 mm) was used in Intamsys FUNMAT HT with the slicing Intamsuite NEO.

### Experimental Approach

The research is divided into three steps (Figure 1). The first two steps were carried out with specimens manufactured in our lab with Roboze Plus PRO FFF and the third step with a set of sheets printed provided by external supplier owner of a Intamsys FUNMAT HT printing machine. The aim of step 1 was to conduct an initial exploration of the feasibility of PEEK hybridization, using FDM-printed sheets and subsequently deforming them with IFS. Previous hybridization work developed by the research group revealed that a suitable compaction of the printed sheets is crucial to prevent breakage during deformation. Thus, in step 2, the printing parameters were adjusted to improve layer adhesion, and a more extensive exploration of the influence of ISF process parameters on part achievement was carried out. Finally, in step 3, using purchased printed sheets, a ISF process parameters were directly tested.

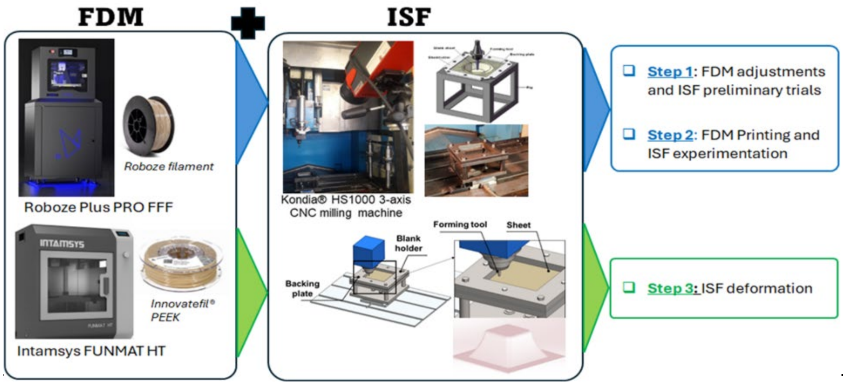



**Fig. 1.** Experimental approach of the research.

### 3D Printing by FDM

Previous hybridization studies showed that suitable compaction of the printed sheets is essential to prevent breakage during deformation, and therefore, adjusting the printing parameters is fundamental. In step 1, specimens were printed using the printing parameters provided by the filament manufacturer, and small variations in printing temperature were applied to analyze the compaction of the resulting parts (Table 1, varied process parameters). Subsequently, in step 2, the main printing parameters, such as printing temperature (PT), flow rate (FR), and printing speed (PS), were adjusted to improve layer adhesion, and a comprehensive exploration was conducted to determine their influence on porosity and thermal properties. In both cases, rectangular specimens measuring 30x20x6 mm were printed, three specimens in step 1 and one for each process parameter combination in step2. Table 1 shows a summary of the printing parameters varied in each step, as well as the fixed parameters used. Considering the high cost of PEEK material, some attempts were made to make smaller specimens to waste less material, but the material overheated too much and caused problems in obtaining the printed parts. The sheets printed by Intamsys, in step 3, were printed with constant printing parameters, as shown in Table 1. In that case, a visual analysis of the quality of the received boards was performed.

**Table 1.** Adjustment of the printing process parameters.

| **Varied process parameters** | | | | |
|---|---|---|---|---|
| **Step** | **# Spec.** | **Printing Temperature (PT) (ºC)** | **Printing speed (PS) (mm/s)** | **Flow rate (FR) (%)** |
| 1 | PP 1.1 | 450 | 36,7 | 0,98 |
| | PP 1.2 | 440 | | |
| | PP 1.3 | 430 | | |
| 2 | PP 2.1 | 470 | 20 | 1 |
| | PP 2.4 | 470 | 36,7 | |
| | PP 2.3 | 440 | 20 | |
| | PP 2.2 | 440 | 36,7 | |
| **Fixed process parameters** | | | | |
| **Machine** | | | **Roboze Plus PRO FFF** | **Intamsys FUNMAT HT** |
| | | | **Step 1 & Step 2** | **Step 3** |
| Infill (%) | | | 100 | 100 |
| Layer height (mm) | | | 0,2mm | 0,2 |
| Top/bottom layer | | | 0 | 0 |
| Outline Perimeter layer | | | 0 | 0 |
| Raster angle (º) | | | +/-45 | +/-45 |
| Bed temperature (ºC) | | | 150 | 145 |
| Chamber Temperature (C) | | | 90 | 90 |
| Drying conditions | | | 12h at 100 °C | 12h at 120 °C |
| Printing Temperature | | | Varied | 400ºC |
| Printing speed | | | Varied | 30 mm/s |

The printed specimens were analysed from two perspectives: a) assessment of qualitative compaction and b) porosity. In the step 1, a qualitative analysis of the filament union was performed to assess void formation at the filament interfaces by inspection visual. Cross-sectional images of printed PEEK samples were acquired using a Nikon SMZ745T stereomicroscope (Nikon, Japan), which provided detailed visualization of the internal structure. In the step 2, the selected specimens were cut in each section, embedded into 40 mm of Axson RSF816 epoxy resin, pre-polished by Struers Knuth Rotor-3 equipment and finished by a Buehler Ecomet sander polishing with alumina powder of 1, 3, and 9.5 microns. The observation of the section was done using a Leica DMR-XA optical microscope with 5x, lüx, and 20x Plan-Apochromat lenses. In the step 3, a visual inspection of the sheets was done.

### ISF Process

The incremental forming experiments were conducted using a Kondia™ HS1000 three-axis CNC milling machine equipped with a fixed sheet-clamping system. The sheets were printed as square and circular plates, with side lengths of 60 mm and diameters of 50 mm, respectively. These dimensions were selected to fit the backing plates and clamping system of the ISF machine while maximizing material utilization. These dimensions were considered to deform incrementally a small conical and pyramidal frustum, using a tool diameter of 6mm.

In the first step, the results obtained in previous research of ISF process parameters used for deforming PEEK commercial sheets of 1 and 2mm thickness were considered [8], due to the success on the depth achieved (higher than 40mm). It is feed rate (FR) 200mm/min, spindle speed (SS) 500 rpm and step down (SD) 0,1mm (Table 2). Two geometries were tested: pyramidal (PF) and conical frustum (CF). Three sheets were printed using the printed process parameters obtained in this step 1 (PT 440ºC, PS 36,7mm/s and FR 98%) but in one of them, a thermal treatment was applied to analyze its influence on forming capabilities. The material was heated from room temperature to 150 °C over a period of 2 hours, followed by a second heating stage from 150 °C to 200 °Cover an additional 2 hours. After reaching 200 °C, the sheet was cooled down to room temperature using a controlled cooling rate of −50 °C per hour. In the second stage the spindle speed (SS) and step down (SD) were varied, being SS 500 -1000 rpm and SD 0,1-0.05mm, respectively (Table 2). Four sheets were printed using the printing process parameters obtained in this step 2 (PT 470ºC, PS 20mm/s and FR 100%).

Distilled water was used on the top surface of each blank to reduce friction between the sheet and the forming tool. This choice was based on the findings of Rosa-Sainz et al. [15], who reported that certain industrial lubricants can negatively affect the polymer structure and its behaviour during forming.

During the forming process, two types of in-process data were recorded: forming forces and surface temperature. The forming forces were monitored using a Kistler® 9257B dynamometric platform mounted on the CNC machine table. The force data was acquired through a DaqBoard® 505 interface and subsequently processed using DaqView® 9.0.0 software. Simultaneously, thermal data were captured using an IRBIS ImageIR 13300 thermographic camera, which acquired infrared images at five-second intervals to monitor the temperature evolution.

## Results

### 3D Printing Results

Fig. 2 shows the results of filaments compaction according to the printing temperature of the parts manufactured in step 1. The results reveal how the increase in temperature strongly overlaps the filaments with each other (P1.1), and at lower temperatures, inter-filament spaces are observed, which could induce potential porosity (P1.3).

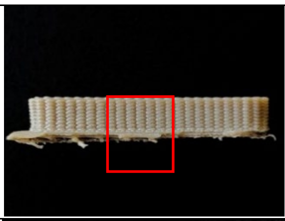
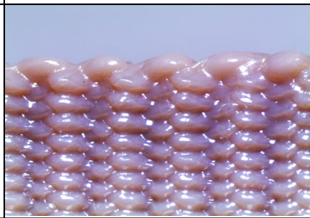
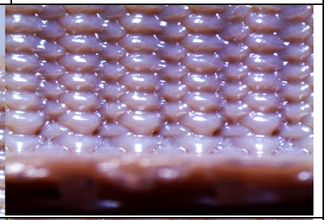
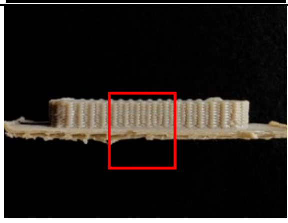
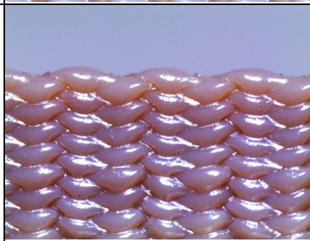
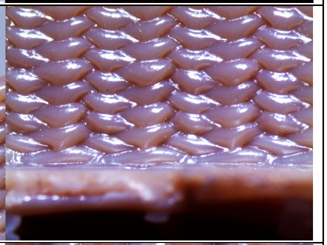
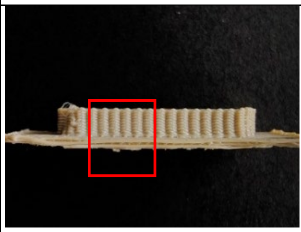
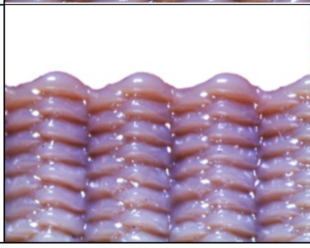
| Specimen | Part | Top | Bottom |
|---|---|---|---|
| PP1.1<br>PT [450ºC] |  |  |  |
| PP1.2<br>PT [440ºC] |  |  |  |
| P1.3<br>PT [430ºC] |  |  |  |

**Fig. 2.** Step 1, printed specimens.

Fig. 3 shows the porosity results of the parts manufactured in step 2. Although few samples were explored, in general, good compaction of the filaments and very low porosity were observed, especially in the central part of the samples.

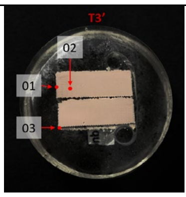
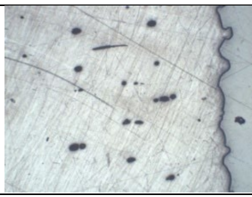
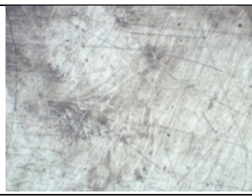
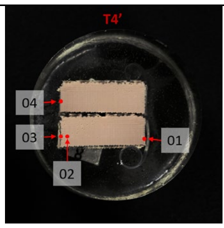
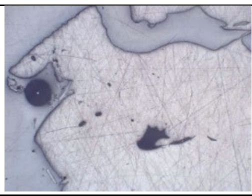
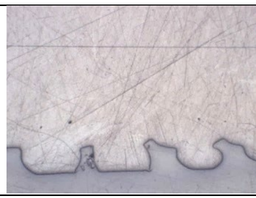
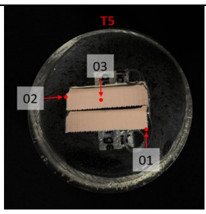
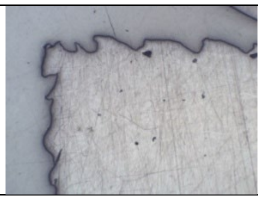
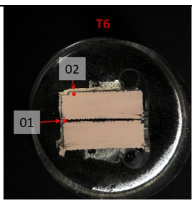
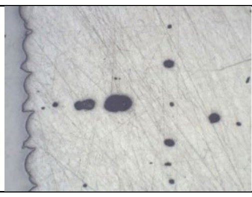
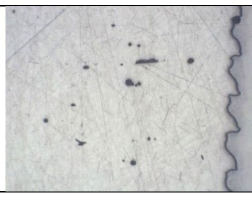
| Specimen | Section | Internal view | |
|---|---|---|---|
| PP2.1<br>Imatges T3'<br>Zone [01, 02]<br>Tª = 470ºC<br>v = 20mm/s |   |  |  |
| | | Zone 1 | Zone 2 |
| PP2.4<br>Imatges T6<br>Zone [01, 02]<br>Tª = 470ºC<br>v = 36.7mm/s |   |  |  |
| | | Zone 1 | Zone 2 |
| PP2.3<br>Imatges T5<br>Zone [01, 03]<br>Tª = 440ºC<br>v = 20mm/s |   |  |  |
| | | Zone 1 | o |
| PP2.2<br>Imatges T6<br>Zone [01, 02]<br>Tª = 440ºC<br>v = 36.7mm/s |   |  |  |
| | | Zone 1 | Zone 2 |

**Fig. 3.** Step 2, printed specimens.

Visual inspection of the printed sheets (Fig. 4) reveals clearly qualitative differences between the sheets produced by each machine. Those printed at a lower temperature (PT 400ºC, Intamsys) exhibit bubbles, warping, and delamination. In contrast, those printed at a higher temperature (PT 470ºC, Roboze) show almost no defects, other than the roughness generated by the support structure used during the printing process or inherent to the filament printing technology itself.

| Intamsys printed sheets PT [400ºC] | | Roboze printed sheets [470ºC] | |
|---|---|---|---|
| Example 1 | Example 2 | Example 3 | Example 4 |

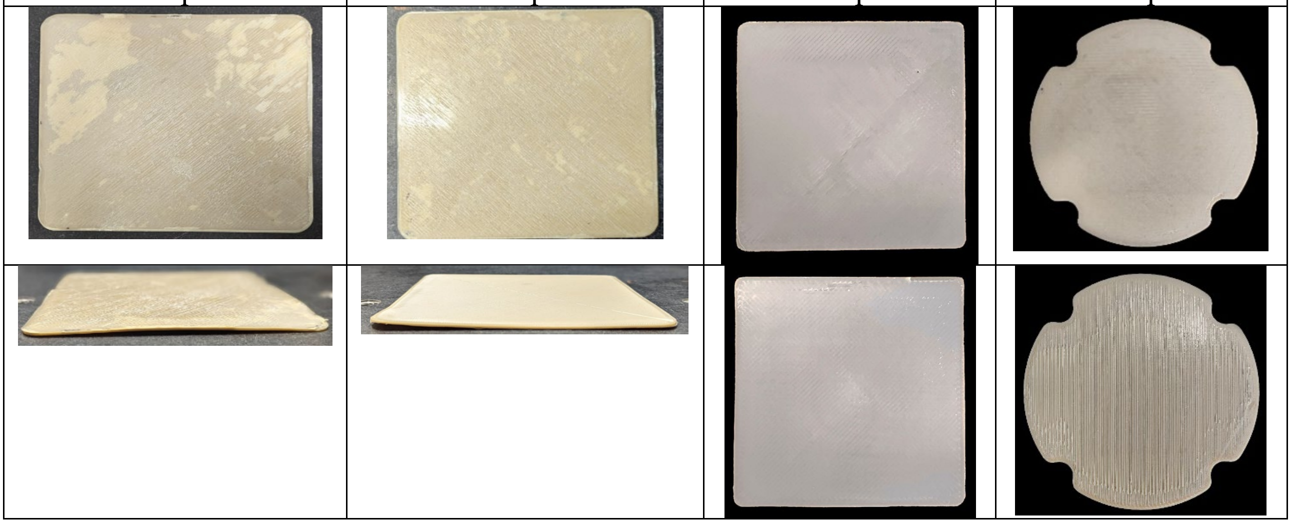


**Fig. 4.** Comparison of printed sheets.

**ISF Process**

The results obtained from the parts deformed using Incremental Sheet Forming (ISF) are summarized in Table 2 and Fig 5. Step 1 and 2 results reveal that only minor variations are observed in the depth values, forming forces, and maximum temperatures achieved. The conical frustum geometry is formed more successfully than the pyramidal geometry, in which a higher incidence of material failure and fracture is observed (Fig. 5). Additionally, the results indicate that when the material was thermally treated, no significant plastic deformation occurs; instead, internal filament breakage was observed, leaving white regions visible along the tool path (Fig 5. and Fig. 6). Furthermore, sheets printed at lower temperatures exhibit filament separation during deformation, with failure occurring primarily at the interfaces between adjacent printed filaments (Fig 6). In contrast, sheets printed at higher temperatures show a more cohesive behavior, where failure is characterized by actual material fracture rather than inter-filament separation.

**Table 2.** ISF results.

| Step | # Spec. | ISF geometry | Feed rate (mm/min) | Spindle (rpm) | Step down (mm) | Thermal Treat. | Fz max. (N) | Z max. (mm) | TºC max (ºC) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | S 1.1 | PF | 200 | 500 | 0,1 | No | 535 | 4.2 | 55 |
| | S 1.3 | CF | 200 | 500 | 0,1 | No | 555 | 5.5 | 60 |
| | S 1.2 | CF | 200 | 500 | 0,1 | Yes | 400 | 0,5 | 24 |
| 2 | S 2.1 | CF | 200 | 500 | 0.1 | No | 525 | 5.2 | |
| | 2 2.1 | CF | 200 | 500 | 0.05 | No | 607 | 5.5 | 65 |
| | S 2.3 | CF | 200 | 1000 | 0.1 | No | 567 | 5 | 80 |
| | S 2.4 | CF | 200 | 1000 | 0.05 | No | 500 | 5.2 | 55 |
| 3 | PC1 | CF | 200 | 500 | 0.1 | No | 400 | 6 | 45 |
| | PC2 | CF | 200 | 1000 | 0.1 | No | 425 | 7 | 61 |
| | PC3 | CF | 200 | 2000 | 0.1 | No | 375 | 6 | 80 |
| | PC4 | CF | 200 | 3000 | 0.1 | No | 225 | 5 | 81 |

In step 3, the forming depth achieved is higher but with fully delamination on the layer in contact with the tool. As expected as higher the SS is, higher the temperature becomes amb lower the load is.

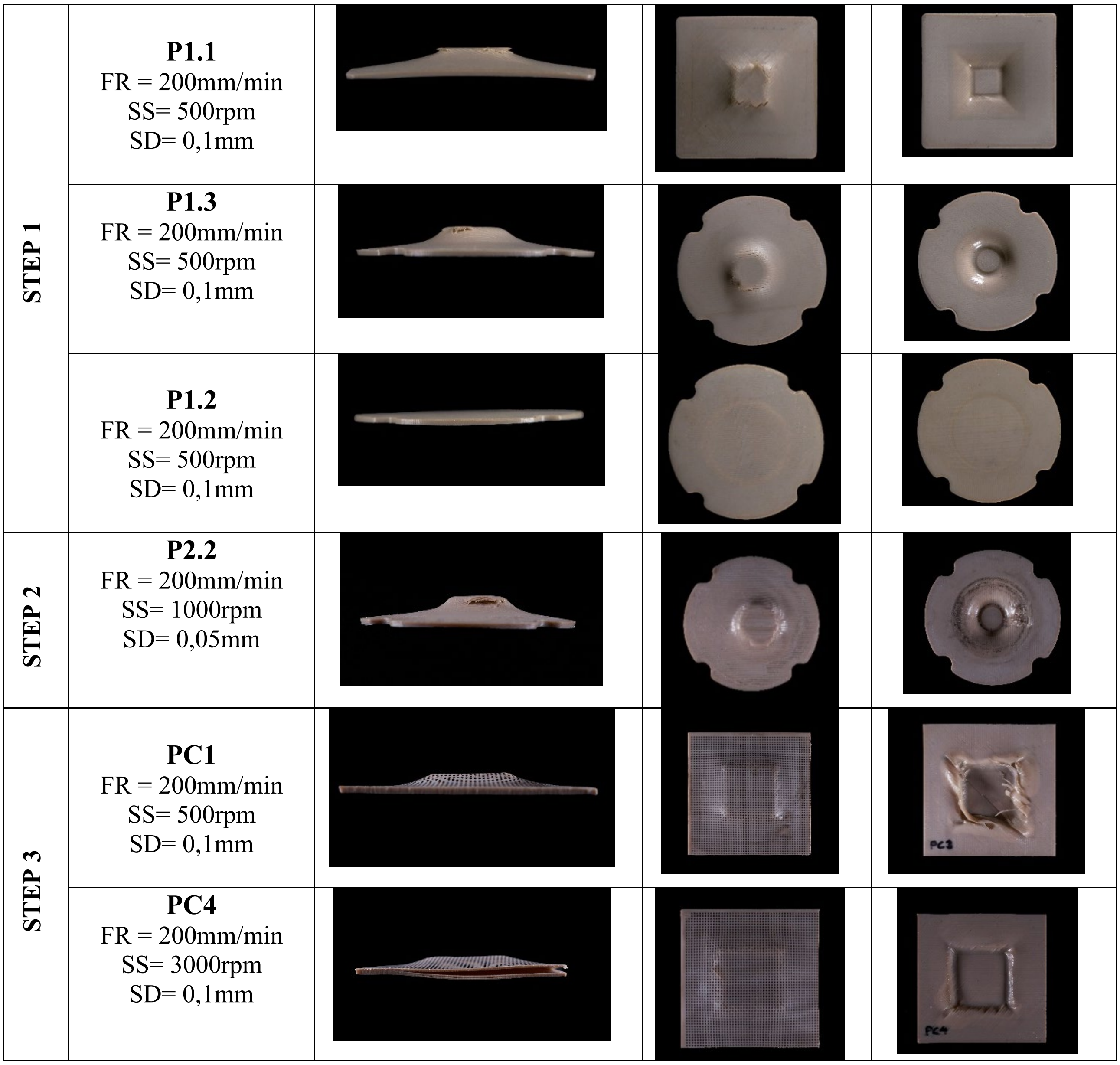



**Fig. 5.** Examples of ISF specimens.

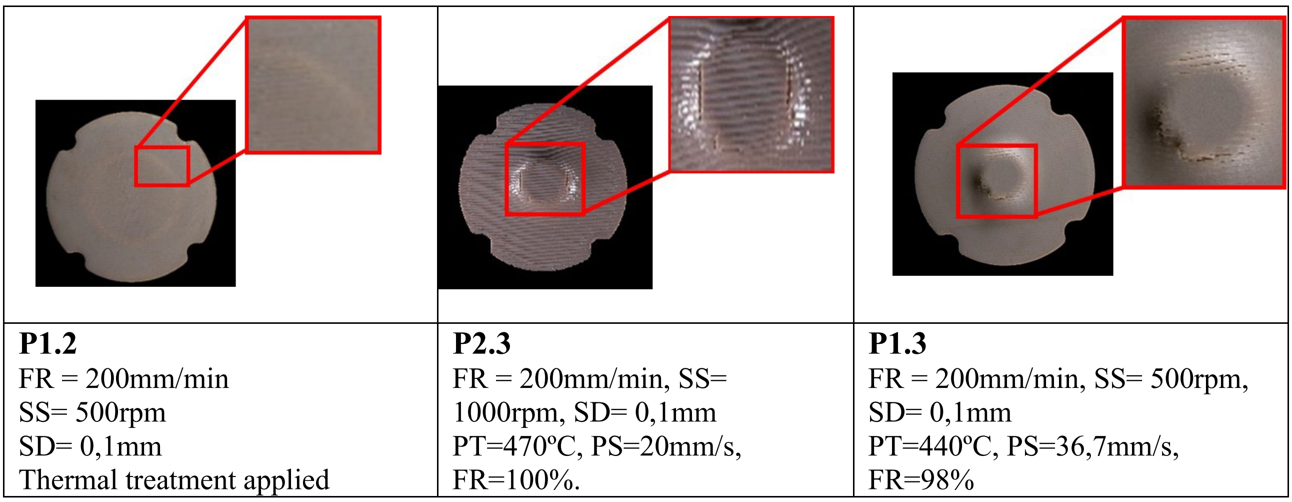



**Fig. 6.** Fracture analysis.

## Conclusion

This study provides an initial assessment of the feasibility of deforming additively manufactured PEEK sheets by Incremental Sheet Forming (ISF) at room temperature. The results indicate that printed PEEK sheets exhibit significant limitations in formability compared to commercial PEEK sheets of equivalent thickness.

Although high printing temperatures enabled the production of sheets with a high degree of solidity, the printing parameters were found to be critical for achieving compact sheets, with the capabilities of the printing equipment playing a decisive role.

Future research should focus on the application of temperature during the forming process to enhance formability, as well as on evaluating the influence of temperature on PEEK degradation and mechanical properties. Furthermore, a more detailed analysis of porosity is required to better understand its effect on the forming behaviour of printed PEEK sheets.

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## References

[1] Ambrogio, G., Denapoli, L., Filice, L., Gagliardi, F., Muzzupappa, M., 2005. Application of Incremental Forming process for high customised medical product manufacturing. Journal of Materials Processing Technology 162-163, 156–162. doi:10.1016/j.jmatprotec.2005.02.148.

[2] Duflou, J.R., Lauwers, B., Verbert, J., Gelaude, F., Tunckol, Y., 2005. Medical application of single point incremental forming: Cranial plate manufacturing, in: Virtual Modelling and Rapid Manufacturing - Advanced Research in Virtual and Rapid Prototyping. pp. 161–166.

[3] Fiorentino, A., Marenda, G.P., Marzi, R., Ceretti, E., Kemmoku, D.T., Lopes Da Silva, J. V., 2012. "Rapid prototyping techniques for individualized medical prosthesis manufacturing." Innovative Developments in Virtual and Physical Prototyping - Proceedings of the 5th International Conference on Advanced Research and Rapid Prototyping 1, pp. 589–594.

[4] Bagudanch, I., García-Romeu, M.L., Ferrer, I., Ciurana, J., 2018. "Customized cranial implant manufactured by incremental sheet forming using a biocompatible polymer." Rapid Prototyping Journal 24, pp. 120–129.

[5] Centeno, Gabriel, Morales-Palma, D., Gonzalez-Perez-Somarriba, B., Bagudanch, I., Egea-Guerrero, J.J., Gonzalez-Perez, L.M., García-Romeu, M.L., Vallellano, C., 2017. "A functional methodology on the manufacturing of customized polymeric cranial prostheses from CAT using SPIF." Rapid Prototyping Journal 23, pp. 771–780.

[6] Yang Z, Chen F, Gatea S, Ou H. Design of the novel hot incremental sheet forming experimental setup, characterization of formability behavior of polyether-etherketone (PEEK). Int J Adv Manuf Technol 2020;106:5365–81. https://doi.org/ 10.1007/s00170-020-05035-0.

[7] Chen LF, Chen F, Gatea S, Ou H. In: PEEK based cranial reconstruction using thermal assisted incremental sheet forming. 236; 2021. p. 997–1004. https://doi. org/10.1177/09544054211045904.

[8] A. Rosa-Sainz, M.L. García-Romeu, I. Ferrer, M.B. Silva, G. Centeno, On the effective peek application for customized cranio-maxillofacial prostheses: An experimental formability analysis, J. Manuf. Process. 86 (2023) 66–84. https://doi.org/10.1016/j.jmapro.2022.12.044.

[9] A. Rosa-Sainz, I. Ferrer, M.L. Garcia-Romeu, G. Centeno, Characterization of plastic formability and failure mechanisms in FDM additively manufactured PETG and PCL sheets, Polym Test 134 (2024).

[10] M.L. Garcia-Romeu, I. Ferrer, C. Pasotti, J. Coma, A. Rosa-Sainz, G. Centeno, Preliminary study on the use of 3D printed biodegradable polymeric sheet for the manufacturing of medical prostheses by SPIF, in: Procedia CIRP, Elsevier B.V., 2022: pp. 76–81. https://doi.org/10.1016/j.procir.2022.06.016.

[11] Hasan, A. & Akhtar, S.S. Hybrid Manufacturing: A Critical Review on the Integration of Metal Additive Manufacturing and Forming 2025, Arabian J. Science and Engng. 1-30.

[12] Hafenecker J, Bartels D, Kuball CM, Kreß M, Rothfelder R, Schmidt M, et al. Hybrid process chains combining metal additive manufacturing and forming – A review. CIRP J Manuf Sci Technol 2023;46:98–115.

[13] Ge T., Li Y., Gao D., Yang C., Li F. Hybridizing additive manufacturing and sheet forming process to manufacture complex components with multi-features: A review. J Manuf Proc 2024;124:345–64.

[14] Ambrogio G, Gagliardi F, Muzzupappa M, Filice L. Additive-incremental forming hybrid manufacturing technique to improve customised part performance. J Manuf Proc. 2019;37:386–91.

[15] Rosa-Sainz A, Centeno G, Silva MB, Vallellano C. Experimental investigation of polycarbonate sheets deformed by SPIF: formability, micro-mechanisms of failure and temperature analysis. J Mater Res Technol 2023;25:7546–65.