Low-Threshold Recycling: From Waste Material to Functional 3D-Printed Parts.

The Purpose of the elaborated Case Studies

Case studies are structured examinations of real-world situations or challenges designed to bridge theory and practice. They are developed both as a research method and as a learning tool to strengthen analytical and problem-solving skills. By engaging with authentic industrial scenarios, students gain practical insight into complex professional environments.

The purpose of this case studies is to encourage active, learner-centred engagement. They support approaches such as problem-based learning by enabling students to work independently or collaboratively, with or without instructor guidance. Through analysing theoretical concepts within realistic contexts, students learn to interpret data and test results, evaluate alternative courses of action, and develop well-reasoned, creative solutions.

This approach is particularly valuable in sectors such as aerospace, defence, and advanced manufacturing, where challenges are multifaceted and solutions are rarely singular. Because multiple valid solutions often exist, guided facilitation is frequently beneficial to help students structure their reasoning, assess trade-offs, and justify their decisions effectively.

Low-Threshold Recycling: From Waste Material to Functional 3D-Printed Parts

Author: Dr. Jens Kruse
IPH – Institut für Integrierte Produktion Hannover gGmbH
https://www.iph-hannover.de

Background:

- Additive manufacturing technologies offer significant potential for reducing material waste and supporting circular economy concepts. However, a large proportion of polymer waste generated from failed prints, support structures, prototypes, and obsolete components is still discarded instead of being reused.
- Within the research project “RecycAligner” (funding reference number 541342162, German Research Foundation DFG), a hybrid extrusion system consisting of a filament extrusion head and a granulate extrusion head was investigated at the IPH gGmbH. The objective was to enable the simultaneous use of virgin material and recycled polymer feedstock within a single additively manufactured component.
- The developed approach allows outer shell structures to be printed from virgin material, ensuring high surface quality and dimensional accuracy, while internal infill structures can be manufactured from recycled material in the form of shredded flakes or recycled granules.
- The concept was demonstrated using an application from dental technology. Nevertheless, the underlying manufacturing strategy is highly relevant for aerospace and defence industries, particularly for the production of transport fixtures, protective devices, assembly jigs, inspection fixtures, and other non-flight-critical tooling components.

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- By combining recycled and virgin materials within one manufacturing process, the approach supports sustainable manufacturing while maintaining functional performance and product quality.

Illustration of the case study

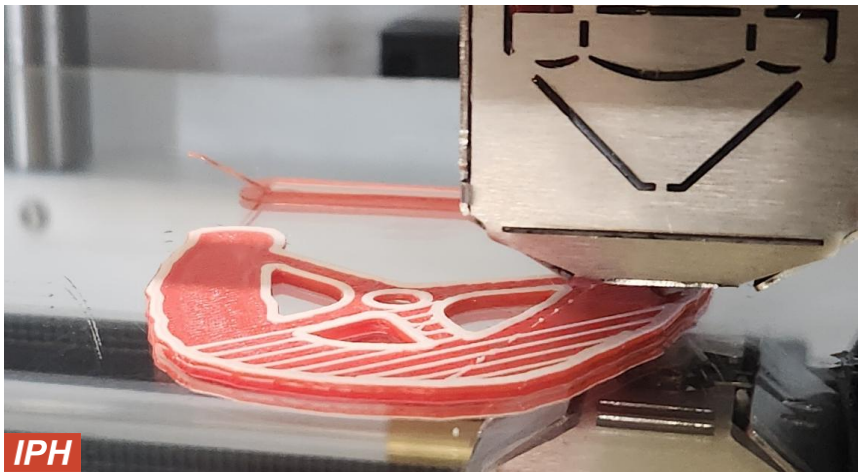


Figure 1: Hybrid additive manufacturing approach using an IDEX system. The outer shell is printed from PLA filament, while the internal structure is manufactured from PLA granulate.

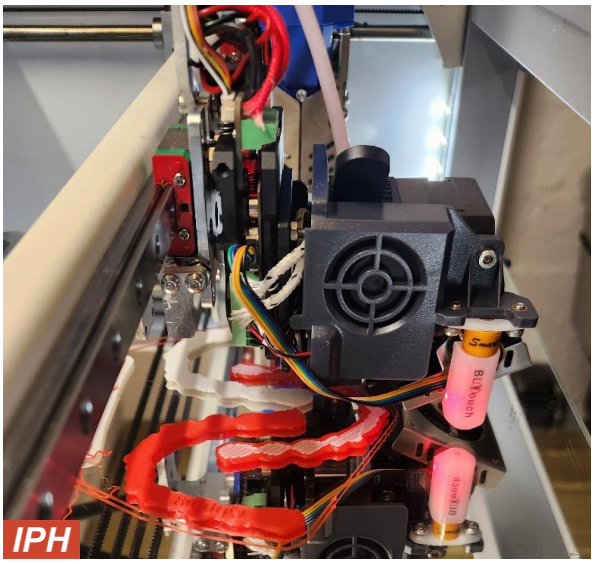


Figure 2: Comparison of different material deposition strategies on an IDEX system using PLA: filament-only printing (red), granulate-only printing (white), and a hybrid approach combining granulate infill with filament outer contours.

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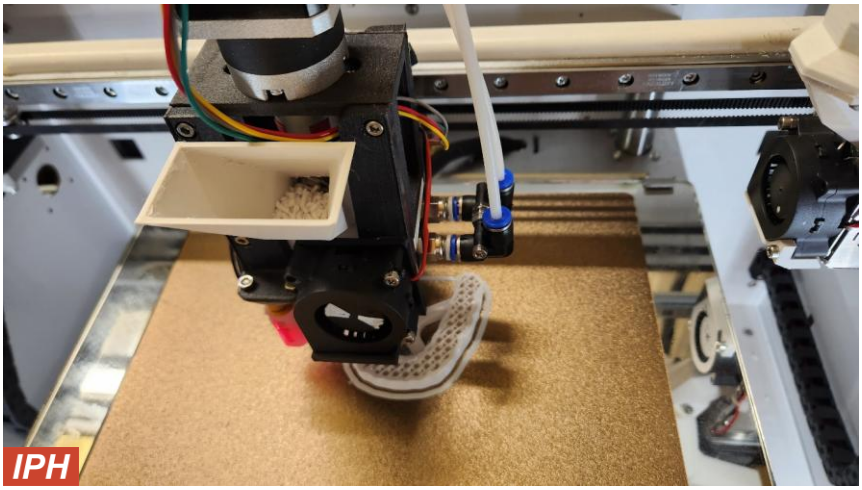


Figure 3: In-house developed water-cooled granulate extrusion system processing virgin PETG pellets during additive manufacturing.



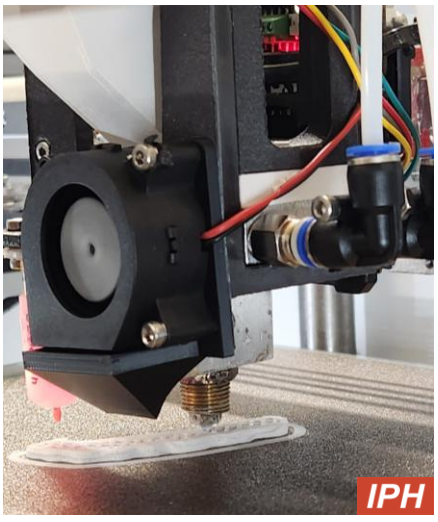


Figure 4: In-house developed water-cooled granulate extrusion system processing recycled PETG flakes directly supplied from the shredding process.

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Technical challenge

The engineering team at IPH had to address several challenges related to the sustainable reuse of polymer waste in additive manufacturing while maintaining the quality requirements of functional engineering components.

Reintegrating Plastic Waste into Manufacturing Processes

Large amounts of polymer waste are generated through failed prints, support structures, prototypes, and end-of-life components. A key challenge was to develop a practical and low-threshold recycling approach that enables this material to be reused for the production of new functional parts rather than being discarded.

Maintaining High Functional and Geometrical Accuracy

The demonstrator application used in this project originated from dental and orthodontic manufacturing. The printed dental models were not merely visual prototypes but functional manufacturing tools used for the thermoforming of orthodontic aligners.
Consequently, the printed models had to achieve high dimensional accuracy, excellent surface quality, and sufficient mechanical stability to ensure that the subsequently thermoformed orthodontic appliances retained the required fit and geometry. The challenge was therefore to maximize the use of recycled material without compromising the demanding quality requirements of the final application.

Processing Different Feedstock Types Within One Manufacturing System

Conventional extrusion-based additive manufacturing systems are typically optimized for either filament or pellet processing. The project investigated how virgin filament, virgin pellets, and recycled polymer flakes could be processed within a single hybrid manufacturing platform.
Furthermore, the developed concept aimed to enable the simultaneous use of different materials within a single component, with virgin material being deposited in quality-critical regions and recycled material being used in non-critical areas.

Selective Material Placement According to Functional Requirements

Different regions of a component have different performance requirements. External surfaces often require high-quality appearance, dimensional accuracy, and reliable mechanical properties, while internal structures mainly provide volume and stiffness.
The challenge was therefore to develop a manufacturing strategy that allows virgin and recycled materials to be selectively deposited within a single part. In the proposed approach, outer contours are manufactured from virgin material, while internal structures and infill regions are produced from recycled material.

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Direct Processing of Shredded Waste Material

Conventional recycling routes for additive manufacturing typically involve several processing steps, including shredding, pelletizing, and filament production before the material can be reused. These intermediate steps increase energy consumption, equipment requirements, processing time, and overall costs. A central objective of the project and its first feasibility study [1] was therefore to investigate whether polymer waste could be directly reused after shredding.
Instead of converting the material into pellets or filament, shredded PETG flakes produced by a cutting mill were processed directly within a granulate extrusion system. The challenge was to establish a reliable manufacturing process despite the irregular shape, varying particle size distribution, and heterogeneous flow behaviour of the recycled flakes.

Feedstock Flow Stability

Unlike standardized pellets, shredded polymer flakes exhibit irregular geometries and bulk densities that significantly influence material transport within the extrusion system.
During the development process, unstable feedstock flow, bridging effects, agglomeration, and temporary blockages at the extruder inlet were observed. Ensuring a continuous and reliable supply of recycled material therefore represented a major technical challenge.

Thermal Creep and Premature Softening of PETG Flakes

One of the most significant challenges was thermal management within the granulate extrusion system. The relatively large temperature difference between the glass transition temperature of PETG and the required extrusion temperature caused unwanted heat transfer from the heater block towards the feed zone. Consequently, PETG flakes began to soften and partially melt before reaching the intended melting region.
This phenomenon, commonly referred to as thermal creep, caused material build-up, increased extrusion torque, unstable material feeding, and occasional clogging of the extrusion system. In severe cases, material jams could overload the extrusion drive and significantly reduce process stability. Within the original proof-of-concept study, only passive and forced-air cooling concepts were investigated. Additional heat sinks and fan-based cooling reduced the problem but did not eliminate it completely during extended printing operations.
Based on the findings of the study, further development work was subsequently carried out at IPH. One promising approach involved the implementation of an actively water-cooled extrusion system to improve thermal isolation between the melting zone and the material inlet. This development was carried out after completion of the published study[1] and represents an important step towards increasing process stability when processing recycled PETG flakes directly from the shredding process.

Establishing a Closed-Loop Manufacturing Process

The project aims to demonstrate a practical circular manufacturing workflow in which previously printed components could be shredded and directly reused as feedstock for new components.
Emphasis was placed on eliminating unnecessary intermediate processing steps and minimizing additional energy consumption and polymer degradation. The challenge was to establish a process chain that combines sustainability, material efficiency, and industrial practicality while maintaining consistent manufacturing quality.

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Transferability to Aerospace Applications

Although the demonstrator application originated from dental technology, the underlying manufacturing concept is highly relevant for aerospace and defence production environments.
The challenge was to evaluate how hybrid-material manufacturing using virgin and recycled polymers could be transferred to non-flight-critical aerospace applications such as transport fixtures, protective covers, assembly jigs, inspection fixtures, and tooling for automated production systems.

Balancing Sustainability, Cost, and Performance

The overall challenge was to demonstrate that environmental sustainability and economic efficiency do not have to be conflicting objectives. The project sought to reduce virgin material consumption, plastic waste generation, energy usage, and material costs while maintaining the quality, functionality, and reliability expected from industrially manufactured components. The resulting process therefore had to balance technical performance, sustainability, and economic feasibility within a single manufacturing strategy.

Detailed solution/ process

Development of a Hybrid Extrusion Manufacturing System

- To enable the simultaneous use of virgin and recycled polymers within a single component, a hybrid additive manufacturing system was developed. The system combines a conventional filament extrusion head with a granulate extrusion head mounted on an independent dual-extrusion (IDEX) platform.
- This configuration allows different materials to be processed according to their functional requirements. Virgin material can be deposited in quality-critical regions such as external surfaces and interfaces, while recycled material can be used for internal structures and infill regions where surface quality is less critical.

The approach combines the dimensional accuracy and surface quality of filament-based extrusion with the sustainability and material efficiency of granulate-based manufacturing.

Direct Recycling of Polymer Waste

- A key objective of the project was to establish a low-threshold recycling workflow with as few processing steps as possible.
- Instead of following conventional recycling routes involving shredding, pelletizing, and filament production, previously printed polymer components were mechanically shredded using a cutting mill. The resulting flakes were used directly as feedstock for the granulate extruder.
- By eliminating intermediate processing steps, the material cycle becomes significantly shorter, reducing energy consumption, process complexity, equipment requirements, and material handling costs.
- This approach demonstrates a closed-loop manufacturing strategy in which waste material can be directly transformed into new functional components.

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Selective Material Placement

- To maintain component quality while maximizing recycled content, a multi-material printing strategy was developed.
- The external contours and visible surfaces of a component were manufactured using virgin material in filament (or in future also pellet) form. These regions determine the dimensional accuracy, surface finish, and functional interfaces of the final part.
- The internal structure and infill regions were manufactured using pellet-based material. Recycled material in flake form can also be used for this purpose. Since these regions mainly provide stiffness and volume, they can tolerate greater material variability while significantly reducing the consumption of virgin polymers.
- This strategy combines the benefits of recycled material use with the quality requirements of industrial applications.

Processing Recycled PETG Flakes

- The feasibility of direct flake processing was investigated using recycled PETG generated from previously printed components.
- Unlike industrial pellets, shredded flakes exhibit irregular geometries and varying particle sizes. As a result, reliable material transport and stable extrusion behaviour represented major challenges.
- Various feed systems and process parameter combinations were evaluated to ensure consistent material flow from the hopper through the extrusion screw and into the melt zone.
- The successful processing of recycled PETG flakes demonstrated that functional components can be manufactured without requiring re-pelletizing or filament production.

Thermal Management and Extruder Development

During the initial proof-of-concept study, significant process limitations were identified when processing PETG flakes:

- The required extrusion temperature of PETG caused heat to propagate from the melting zone towards the material inlet. This resulted in premature softening of the flakes before they reached the intended melting region. The phenomenon, known as thermal creep, led to material accumulation, unstable feeding behaviour, increased extrusion torque, and occasional clogging.
- The original experimental setup relied on passive heat sinks and forced-air cooling to mitigate these effects. Although these measures improved process stability, feedstock blockages continued to occur during extended print jobs.
- Based on the insights gained during the study, additional development work was carried out at IPH after completion of the published research. One major improvement was the implementation of an actively water-cooled extrusion system. The water-cooling concept was specifically designed to improve thermal separation between the heater block and the feed zone, thereby reducing premature softening of the recycled flakes and improving long-term process stability.

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Validation Through Dental Model Manufacturing

- To validate the manufacturing approach, dental and orthodontic models were selected as demonstrator components.
- These applications impose demanding requirements on dimensional accuracy and surface quality because the printed models serve as manufacturing tools for subsequent thermoforming processes. Orthodontic aligners and retainers are formed directly over the printed models, making geometric accuracy essential for the final product.
- Optical 3D scanning was used to compare the printed models with the digital CAD reference geometry. The results demonstrated that recycled PETG processed through fused granular fabrication can achieve the dimensional accuracy required for dental and orthodontic applications.
- This validation provided proof that directly recycled material can be used to produce precision components.

Transfer to Aerospace Manufacturing Applications

Although the demonstrator originated from dental technology, the developed manufacturing concept is directly transferable to numerous aerospace manufacturing applications. Potential applications include:

- Transport fixtures for sensitive components
- Protective covers for sensors and equipment
- Assembly jigs and positioning aids
- Inspection fixtures
- Tooling for automated manufacturing systems
- Robot end-effectors and gripper components

In these applications, high-quality outer surfaces can be manufactured from virgin material while large internal volumes are produced from recycled feedstock, enabling significant material savings without compromising functionality.

Establishing a Semi-Closed-Loop Manufacturing Concept

The overall process demonstrates a practical Semi-closed-loop manufacturing strategy for material-extrusion-based additive manufacturing. The workflow consists of:

- Manufacturing functional parts.
- Collecting end-of-life components, failed prints, and production waste.
- Shredding the material into reusable flakes.
- Directly processing the recycled flakes through a granulate extrusion system.
- To improve quality, virgin material could be added.
- Manufacturing new functional components.

By combining selective material placement, direct flake processing, and hybrid extrusion technology, the project demonstrates how polymer waste can be transformed into functional engineering products while reducing resource consumption and supporting circular manufacturing principles.

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Results and Benefits

- The project demonstrated the feasibility of producing functional additively manufactured components from recycled polymers using a low-threshold recycling approach based on fused granular fabrication (FGF).
- The developed manufacturing concept showed that polymer waste can be mechanically shredded and directly reintroduced into the additive manufacturing process without intermediate pelletizing or filament production. By combining recycled feedstock with virgin material within a hybrid extrusion system, high-quality functional components can be manufactured while significantly reducing the consumption of new raw materials.
- The investigation also identified key technical limitations associated with the direct processing of recycled PETG flakes, particularly regarding feedstock transport and thermal management. These findings provided valuable insights for the subsequent development of water-cooled extrusion systems aimed at improving process stability.

Benefits Achieved

- Successful demonstration of direct flake-to-part manufacturing without pelletizing or filament production.
- Reuse of polymer waste within a closed-loop manufacturing workflow.
- Reduction of virgin material consumption through selective material placement.
- Preservation of surface quality and dimensional accuracy in quality-critical component regions.
- Validation of recycled PETG for precision applications requiring high geometrical accuracy.
- Reduced process complexity compared to conventional recycling routes.
- Lower material costs through the utilization of recycled feedstock.
- Demonstration of a scalable approach for circular manufacturing.
- Transferability to aerospace tooling, fixtures, and production support applications.
- Identification of thermal management requirements for future large-scale industrial implementation.

Literature:

[1] Kruse, J.; Stonis, M.; Barasinski, J.; Stangl, F.K.; Sabbagh, H. Sustainable Production of Dental and Orthodontic 3D Models Through Fused Granular Fabrication of Recycled Polymers. Bioengineering 2026, 13, 558. https://doi.org/10.3390/bioengineering13050558

Competence unit coverage:

	AILEEN competence units	Covered CU
AI_01	Inspection: Non-Destructive Testing (NDT) in Additive Manufacturing for metals and polymers	✅
AI_02	Inspection: Metrology in Additive Manufacturing for metals and polymers	✅
AI_03	Inspection: Inspection of AM parts. Material Quality	✅
AG_02	Green: Sustainable Design and Environmental Compliance in Aerospace and Defence	(✅)

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