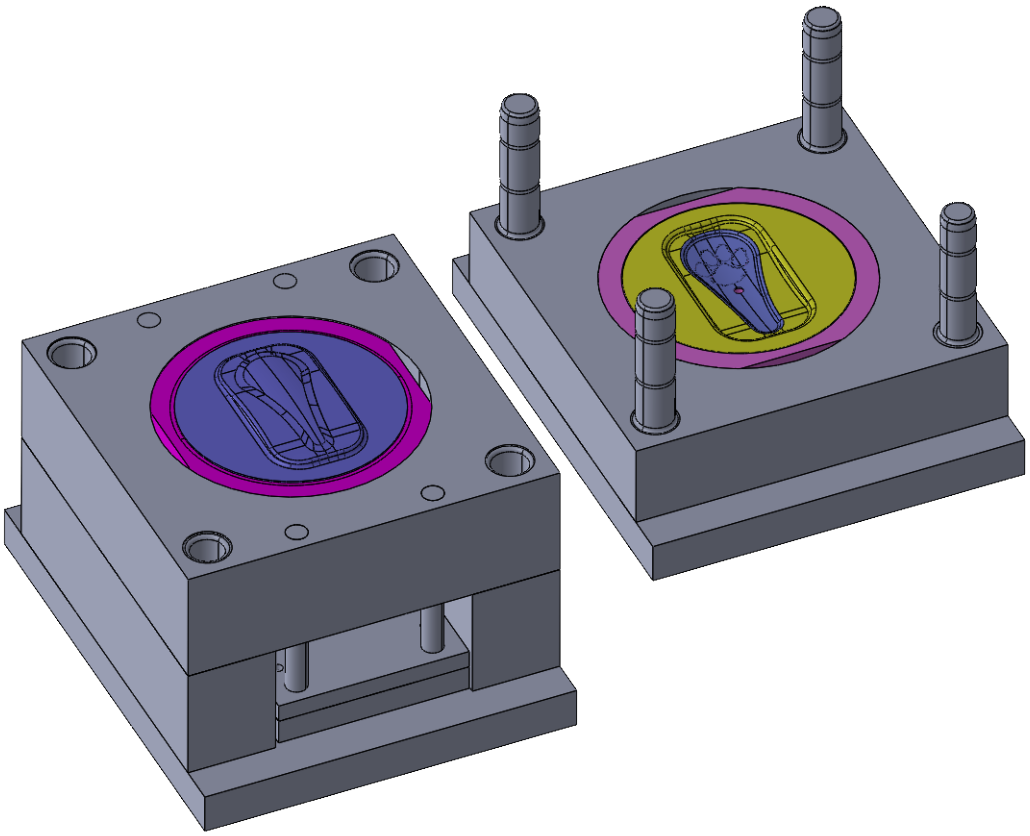
SME Digital Manufacturing Challenge 2025

A Novel Sustainable Low-cost Tooling via Hybrid Manufacturing Technology



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1. Executive Summary

Integrating plastic waste into hybrid manufacturing, which combines additive manufacturing with conventional processes for tool production, particularly in low-volume manufacturing, can significantly enhance the sustainability of tool-making technology—a crucial feature of this proposed approach. The necessity for flexibility in tooling is heightened by the requirements of low- to medium-volume production, where the development of new tools using conventional methods such as CNC milling, turning, grinding, and EDM is resource-intensive and time-consuming. Conventional tooling methods, while effective, often lead to high consumption of materials, energy, and labor, mainly when tools are no longer usable post-production and must be recycled or repurposed. This high resource usage and waste cycle highlights the urgent need for more sustainable manufacturing practices. As industries face ever-growing competition fueled by technological advancements, there is an increasing demand for innovative tooling solutions that enable rapid, cost-effective manufacturing and prioritize environmental sustainability to maintain a competitive edge.

The Hybrid Modular Tooling (HMT) system presents a sustainable and efficient solution tailored for rapid customization in low-volume production settings. This system combines a durable steel "Mother Tool" with versatile 3D-printed polymer inserts, which can be made from plastic waste enhanced through a Polymer Injection Forming (PIF) process. Adding metal lamination to the inserts not only refines their surface quality but also improves their mechanical and thermal resilience, enabling them to endure higher pressures and temperatures. This multi-material modular approach minimizes waste and lowers operational costs by incorporating recycled materials for polymer inserts or utilizing a shell structure reinforced with a cement-plastic waste mixture. The modular design allows inserts to be easily replaced and facilitates recycling, enabling their reuse in producing new inserts. Furthermore, the HMT system incorporates advanced functionalities like conformal cooling channels and embedded sensors, enhancing tool performance and monitoring capabilities, which conventional tooling methods cannot cost-effectively achieve. This innovative integration of recycled materials and advanced manufacturing techniques positions the HMT system as a pivotal advancement in meeting the dual goals of environmental responsibility and manufacturing agility.

2. Industry Overview

3D-printed polymeric molds are now widely used in applications like injection molding, casting, thermoforming, and composite fabrication, as well as in specialized fields such as biomedicine, soft lithography, and tissue engineering [1], [2], [3], [4], [5], [6], [7], [8]. These applications benefit from AM's flexibility and speed, allowing for quick iteration and creating complex geometries that are challenging to achieve with conventional mold-making methods. Additionally, AM is ideal for low-volume production where the quick turnaround and lower upfront investment are valuable [9].

The sustainability benefits of AM technology in tooling production underscore its potential to enhance global manufacturing competitiveness by supporting local producers. While the economic advantages are substantial, the environmental benefits emphasize the importance of balancing economic and environmental performance through strategic trade-offs. These findings also highlight the need for technological advancements in AM that can drive greater sustainability, ultimately expanding its positive impact on the tooling industry [10]. However, AM techniques, particularly fused FDM, face significant limitations in tool production. The mechanical strength of common polymers is generally lower, reducing durability and load-bearing capacity, which restricts their utility in high-stress or high-temperature applications.

FDM parts exhibit anisotropic strength due to the layer-by-layer construction, making them prone to fracture or failure under repeated use. These tools also often lack the surface finish quality required for industrial-grade applications, necessitating time-intensive post-processing to improve smoothness [11], [12], [13], [14], [15]. This creates a significant gap in tooling solutions that support rapid customization and efficient low-volume production without the high costs of conventional methods while also enabling the use of recycled materials for tool fabrication and emphasizing the sustainability of tool-making processes.

Therefore, identifying low-cost tooling methods to overcome these limitations would be highly beneficial. Hybrid manufacturing offers a potential solution for this need. Hybrid manufacturing combines additive, subtractive, and transformative techniques to maximize each method’s strengths while minimizing individual limitations, offering significant advantages like improved surface quality, enhanced dimensional accuracy, and faster production times. This approach allows for material flexibility, enabling multiple materials within a single part to meet varied property requirements. By integrating these processes on a single platform, hybrid manufacturing reduces setup and handling time, streamlines production, and allows for cost-effective customization. These benefits are particularly valuable in low-volume, high-value sectors where efficiency, precision, and adaptability are essential [16].

A proposed new tooling solution is based on the unique integration of a multi-material modular tool design and an innovative hybrid manufacturing approach. The proposed design is necessary because it integrates multi-material modular design with hybrid manufacturing to overcome the abovementioned deficiencies. This integration allows for the rapid and cost-effective production of durable, high-quality tools adaptable to various manufacturing needs. The design's novelty and effectiveness in addressing these market needs are further supported by initial case studies demonstrating promising performance, especially in prototyping and low-volume production of injection molded parts.

The critical timelines for this project include the anticipated reductions in tool cost and lead time. The technology will benefit industries requiring frequent design changes or small production runs, such as the automotive and aerospace sectors, where conventional tooling costs and lead times are prohibitive. The community and social impact include increased efficiency and reduced costs, leading to more innovative products benefiting consumers and businesses at lower prices.

Additionally, the sustainability aspect of the proposed Hybrid Modular Tooling (HMT) system is significantly enhanced by incorporating environmentally conscious practices such as utilizing recycled plastics in the AM process and making the main inserts. This approach reduces waste and promotes the circular economy by repurposing plastic waste into valuable tooling components. Furthermore, the proposed design involves an innovative method where the 3D-printed shell structures can be filled with a composite mixture of cement and plastic waste, leveraging the durability of cement while reducing environmental impact through the reuse of plastics. This sustainable manufacturing method aligns with global efforts to reduce industrial waste and promotes adopting green manufacturing practices [17], [18]. The HMT system sets a new standard for sustainability in the tooling industry and addresses conventional tooling methods' technical and economic challenges. Industries like the automotive and aerospace sectors, which require frequent design changes or small production runs, will benefit from the technology. Higher productivity and lower expenses result in more creative products that benefit businesses and consumers at lower costs, impacting the community and society. Additionally, using recycled plastics in the AM process, the HMT system advances the circular economy, significantly lowering waste and improving environmental sustainability.

3. Design, Functionality, and Durability

One key innovation in the HMT method is the multi-material modular tool design, which includes a tool base, or "Mother Tool," paired with interchangeable inserts. The Mother Tool, typically made of steel or aluminum using conventional machining methods, incorporates essential tooling system features to allow reuse across various applications. Inserts, designed with a multi-material approach, are tailored to meet the required performance and functionality of the final tool. The main structure of each insert is created with low-cost, polymer-based additive manufacturing. It is then laminated with a sheet metal layer through the Polymer Injection Forming (PIF) process. PIF is an innovative hybrid manufacturing method that combines sheet metal forming with polymer injection molding to produce metal-polymer composite structures in one step. A metal sheet is located inside a mold, where the polymer shapes the metal into the desired form [19]. The schematic of the PIF process is shown in Figure 1.

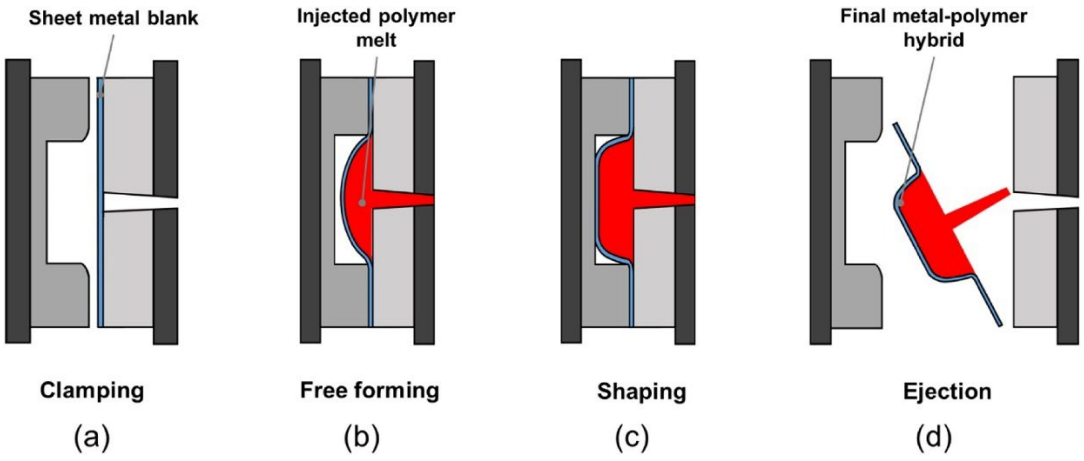

Figure 1: Schematic of the PIF process and its sequences [19]

This sheet metal layer not only improves surface finish but also strengthens the mechanical and thermal properties of the inserts, allowing them to handle higher pressures and temperatures. This modular, multi-material design approach for inserts enables cost-effective manufacturing while preserving the high-performance standards of conventional steel or aluminum tools.

The multi-material design of the HMT tooling system also allows for integrating advanced functionalities that are difficult or expensive to achieve with conventionally manufactured tools. Using 3D printing for the inserts enables the inclusion of conformal cooling channels, which significantly enhance the cooling efficiency of the tool. The 3D-printed insert is first mounted onto the mold base, after which a sheet metal blank is positioned between the mold halves. The

polymer melt injection process deforms the sheet metal upon clamping, bonding it to the printed part through a heat-activated adhesive layer or mechanical fasteners. This hybrid approach enhances the tooling's durability and functionality and enables efficient, high-quality production tailored to specific tool design requirements. The HMT manufacturing steps are shown in Figure 2.

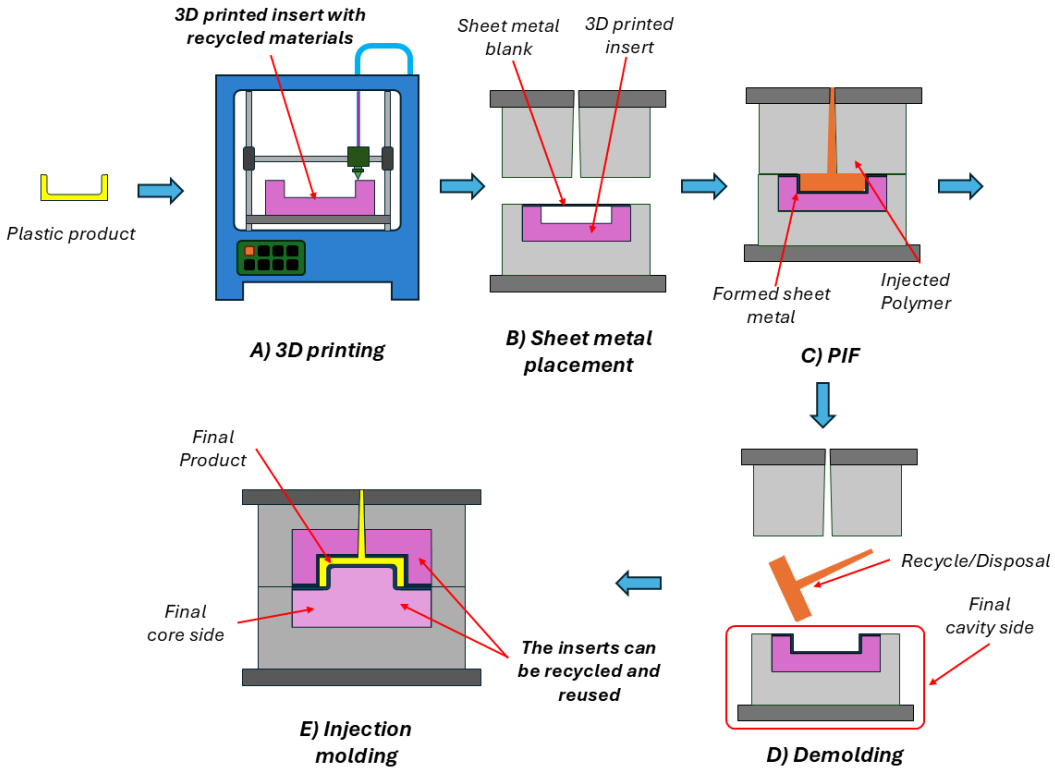

Figure 2: Schematic of the HMT manufacturing steps – Recycled materials can be used for inserts and can be recycled again after production and reused

A shoehorn-shaped product featuring a Tiger Paw design (Clemson sign) was created using CAD software as a case study. This design serves as a rigorous test for the precision and capability of the manufacturing technology, as it incorporates both the curved surfaces characteristic of a shoehorn. To achieve a high-quality finish and ensure dimensional accuracy, the sealing surfaces of the inserts were meticulously designed to align with the flat base mold. This alignment was critical to achieving a flat, uniform surface on the final laminated inserts, essential for effective sealing and part performance. A pocket shape was incorporated around the part in the mold design to address potential curvature issues in the sealing surface. This adjustment reduced the curvature of the sealing surface, allowing the sheet metal to deform more effectively during the PIF process and ensuring superior sealing in the final HMT system. The schematic design and images of the inserts and the Tiger Paw details are shown in Figure 3.

The design of the 3D-printed insert was optimized to include a 1 mm step matching the thickness of the sheet metal. This feature precisely positioned the blank sheet metal on the insert, ensuring accurate alignment and deformation during the PIF process. The result was a top surface of the laminated sheet metal that perfectly aligned with the base mold, maintaining a seamless transition on both sides of the assembled tooling system. Two flat surfaces were incorporated on the sides of each insert for practical assembly and operation.

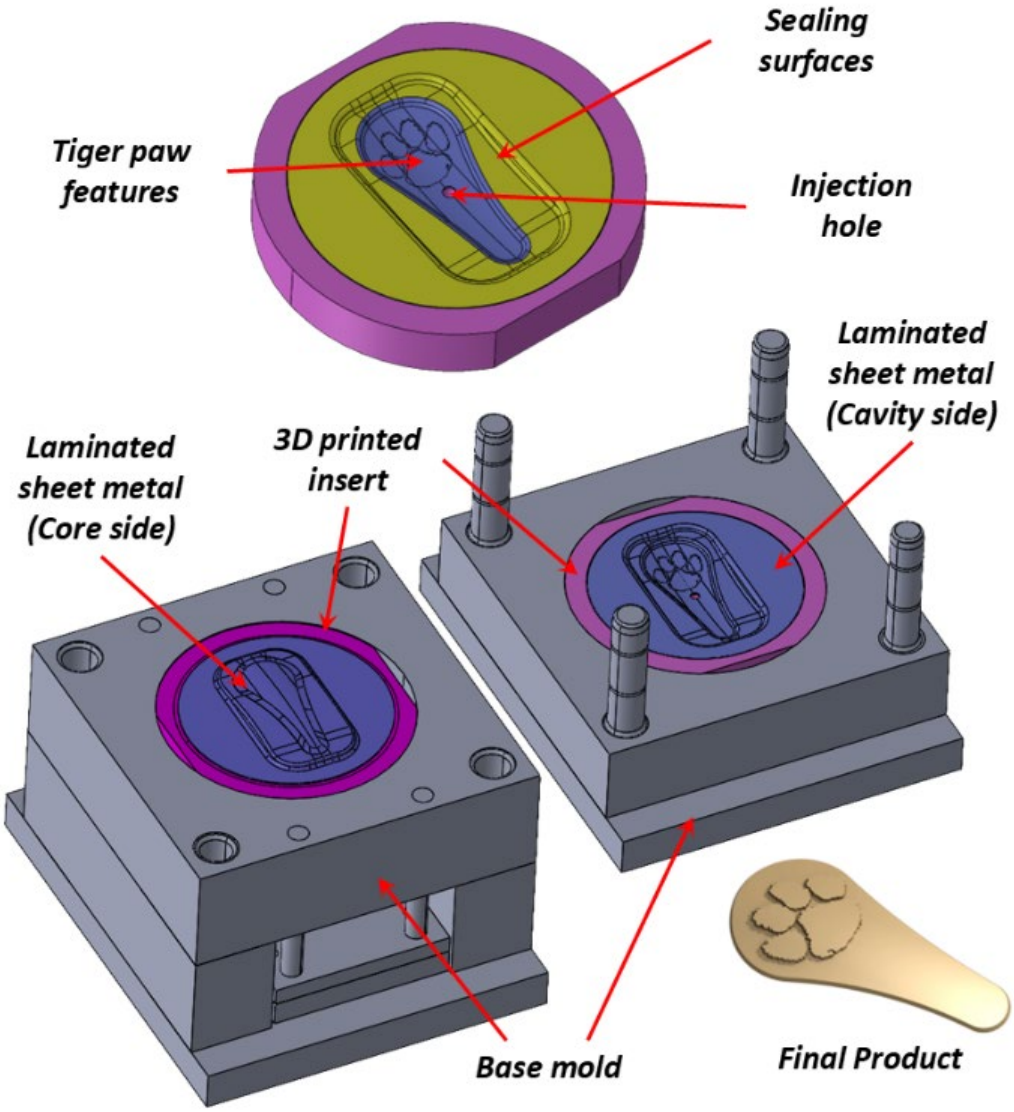

Figure 3: Assembled design of HMT inserts with base mold and the final product

These features simplified the assembly and removal of the inserts from the base mold while facilitating the alignment of the two inserts during the final injection molding step to produce the finished part. This case study highlights the effectiveness of the HMT system in making complex, high-precision components, demonstrating the system's potential for diverse

applications in prototyping and low-volume manufacturing. The final injected product and HMT dimensions are shown in Figure 4.

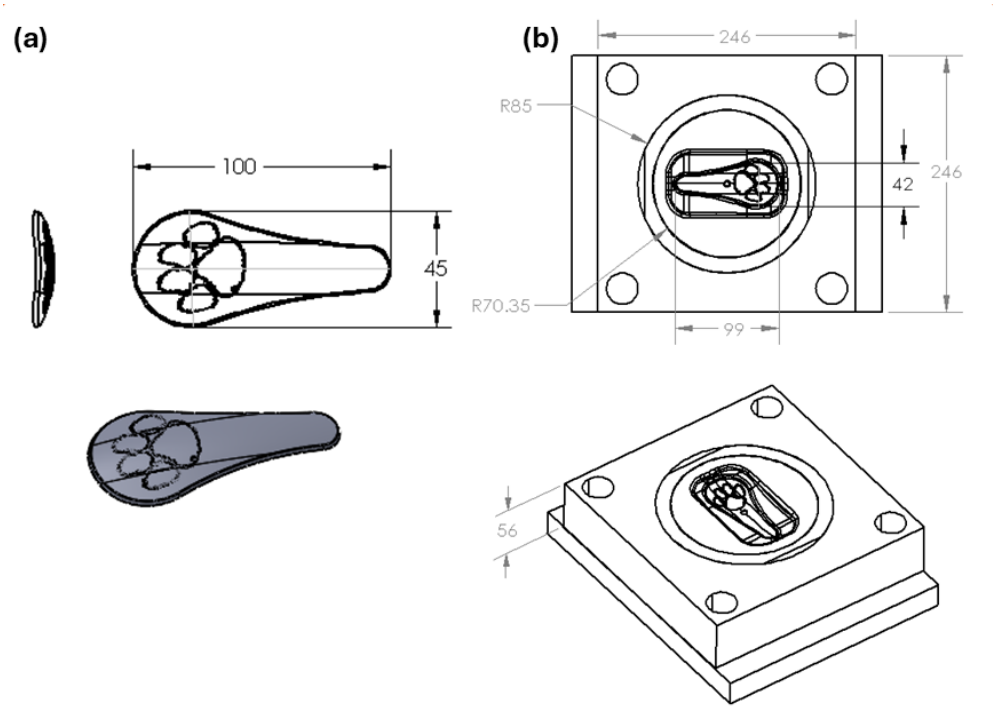

Figure 4: a) Final Product dimensions b)HMT dimensions

In the first step of the process, the inserts were 3D-printed using an Ultimaker S Series printer. The printing parameters, optimized to ensure the inserts' structural integrity and surface quality, are detailed in Table 1. A critical aspect of this step was ensuring the strength and durability of the 3D-printed inserts, which serve as the core structure for the laminated tool components. To achieve this, an infill percentage of 60% was selected. This choice balances material efficiency with mechanical robustness, providing sufficient internal support to withstand the subsequent PIF process without compromising the overall production costs or time. Images of the 3D-printed inserts, showcasing their quality and design features, are presented in Figure 5.

Table 1: 3D printing setting

Settings	***ABS***
Layer height	*0.2 mm*
Wall thickness	*2 mm*
Infill percentage	*60%*
Printing speed	*50 mm/s*
Nozzle temperature	*240 °C*
Bed temperature	*85 °C*

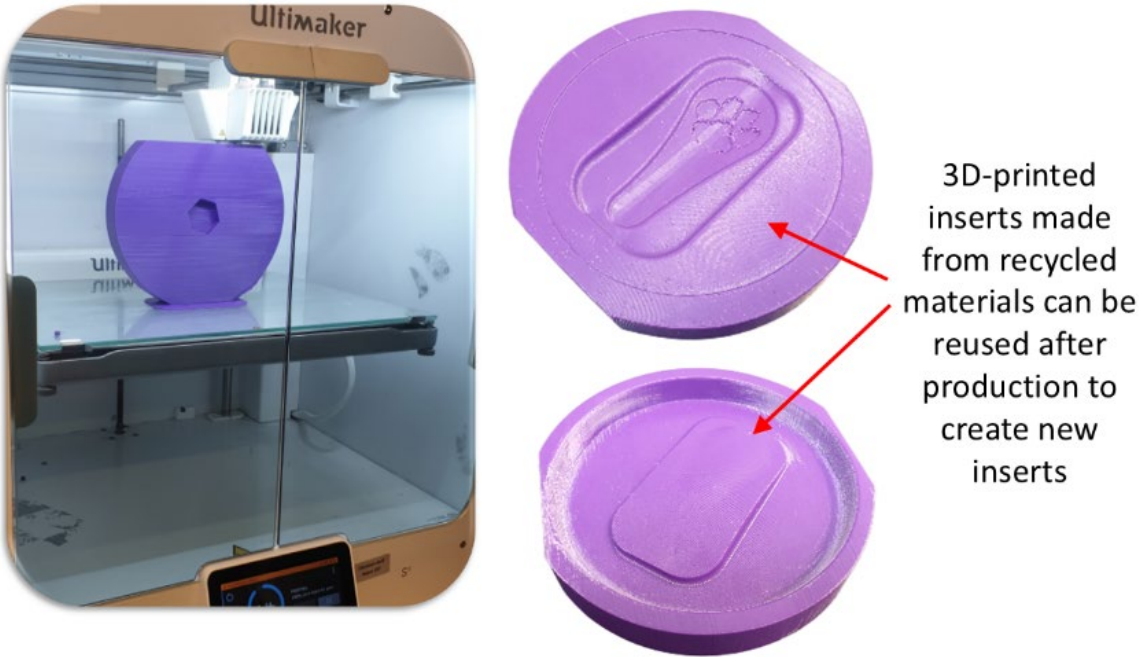

Figure 5: 3D-printed inserts for the HMT process can be made using recycled materials and recycled and reused to produce new sets of inserts.

In the next step, heat-activated adhesive tapes were applied to the back side of the aluminum sheet, which was then carefully positioned on top of the 3D-printed insert. This laminated structure, composed of the aluminum sheet and the 3D-printed insert, was then integrated into one side of the base mold in preparation for the PIF process. Proper alignment and positioning of the assembly were ensured, which is crucial for achieving the desired deformation of the aluminum sheet during injection. The PIF process was carried out using the Engel VC 200/30 injection molding machine, ensuring high precision and consistency. The injection parameters, outlined in Table 2, provide a detailed overview of the conditions required for effective injection and forming.

Table 2: Injection process parameters for PIF

Settings	***PP***
Shot volume	*50 cm^3*
Melt temperature	*200 °C*
Mold temperature	*32 °C*
Clamp force	*150 kN*
Cool time	*74 s*
Holding pressure time	*5 s*
Injection pressure	*137 MPa*

After completing the Polymer Injection Forming (PIF) process, the laminated aluminum sheet can be secured to the 3D-printed insert using small screws, ensuring a stable and durable attachment. The screw attachment provides additional support to the bond formed by the Thermal Bonding Film, reinforcing the connection between the aluminum sheet and the printed insert, which enhances the overall strength of the insert. The same process is applied to the core side of the inserts, ensuring uniform bonding and assembly across all sides of the laminated tool. Once the core side is secured, the final two sides of the inserts are assembled in the base mold. After completing these assembly steps, the final product is injected, with the laminated aluminum sheet securely attached to the 3D-printed inserts, ready for its intended application. Some images illustrating these assembly steps, showing the process and final setup of the inserts within the mold, are provided in Figure 6.

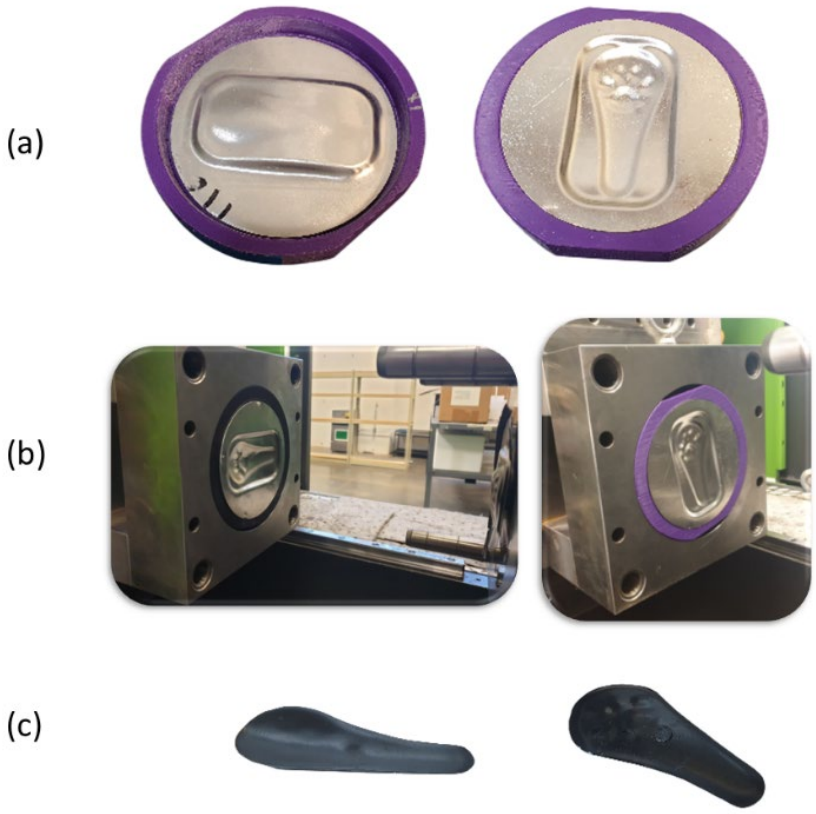

Figure 6:(a) HMT inserts (b) Assembled inserts in base mold (c) Final injected part

As previously discussed, an alternative approach to enhance sustainability and environmental friendliness involves utilizing a shell structure for the 3D-printed insert and filling it with a mixture of cement and plastic waste. This concept has been investigated, and an image of the HMT tool filled with cement and plastic waste is presented in Figure 7.

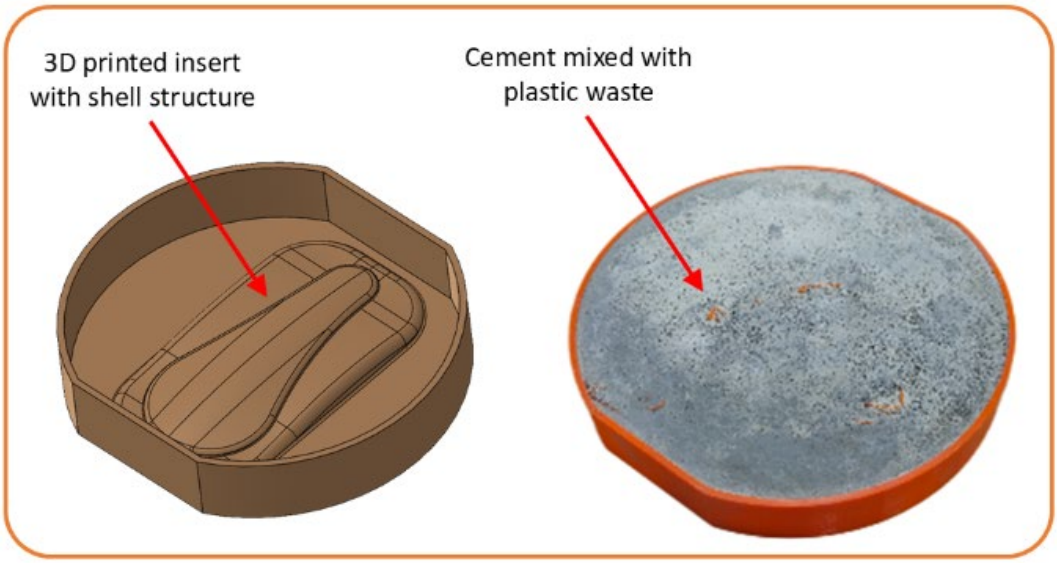

Figure 7: The cavity side of the HMT tool features a 3D-printed shell structure reinforced with a mixture of cement and plastic waste.

4. Design Integration and utilization of DDM materials and processes

By combining Additive Manufacturing with conventional techniques, the Hybrid Modular Tooling system improves sustainability and performance, marking a substantial advancement in tooling technology. This system combines metal lamination with 3D-printed polymer inserts. In addition to cutting production costs and times, this combination addresses the high standards needed for tooling applications in sectors where mechanical, thermal, and surface qualities are important.

A degree of design freedom and cost-effectiveness that is impossible with conventional methods alone is introduced using 3D printed inserts in the HMT system, in contrast to traditional tools that frequently rely only on metals and require intricate and expensive processes to achieve detailed features. Because it can quickly and effectively create complex geometric shapes, the FDM process is used for the polymer inserts and is perfect for custom, low-volume production runs. This method provides considerable waste reductions and design modification flexibility, essential for a quick market response. The HMT system can use other AM techniques like SLA (Stereolithography) and SLS (Selective Laser Sintering). More thick laminated sheets can be used, and post-processing operations like milling can be carried out to enhance this method's capacity to produce precise edges and corners or intricate features that are impossible to create with metal-deformed sheets.

The modular design of the HMT also improves end-of-life recyclability and serviceability. The main tool body can last longer thanks to easily replaceable parts like damaged inserts. Recycling materials like polymers and laminated metal at the end of their useful lives can lessen their negative effects on the environment and advance a circular economy. These features guarantee that the HMT system substantially contributes to environmental preservation, which aligns with international sustainability initiatives and addresses the technical and financial difficulties related to conventional tooling methods.

5. Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

The HMT system is versatile enough for both large- and small-scale applications, and it is especially well-suited for small to medium production volumes based on the tool's usage. It integrates smoothly with existing manufacturing workflows and digital fabrication technologies by leveraging digital and physical infrastructures. This innovative method enables the creation of smart tooling by embedding sensors both within the tool and behind the laminated sheet metal. Such integration allows for real-time monitoring and data collection during manufacturing, boosting the system’s efficiency, precision, and adaptability. A central element of this approach is using printed, electronic sensors engineered to flex and conform to the laminated sheet metal, ensuring they continue to operate effectively despite complex geometries and deformations. This guarantees a smooth integration that does not affect the tool’s mechanical or thermal properties. Alternatively, sensors can be strategically placed on the 3D-printed insert, concealed under the laminated layer, protecting sensitive electronic components while preserving the tool’s structural integrity. Ultimately, these embedded sensors empower manufacturers to gather live data, detect potential issues early, and adjust production parameters on the fly to maintain consistent quality and minimize material waste. These enhancements add a layer of intelligence and functionality to the system without sacrificing its modular and cost-effective design, making it versatile enough for various industries and applications.

Figure 8 illustrates the schematic of the HMT system, showcasing how sensors can be seamlessly integrated into the tool’s design. Combining hybrid manufacturing with smart sensing capabilities represents a significant leap forward in the evolution of advanced manufacturing technologies, offering efficient, cost-effective solutions capable of meeting the demands of Industry 4.0. The modular design of the HMT system addresses a crucial issue of serviceability. Upgrading or replacing specific parts of a tooling system without replacing the entire setup is a big benefit because it prolongs the manufacturing tools' lifetime and reduces waste. This modularity makes it possible for system components to be serviced separately, which is essential for preserving uninterrupted production cycles and

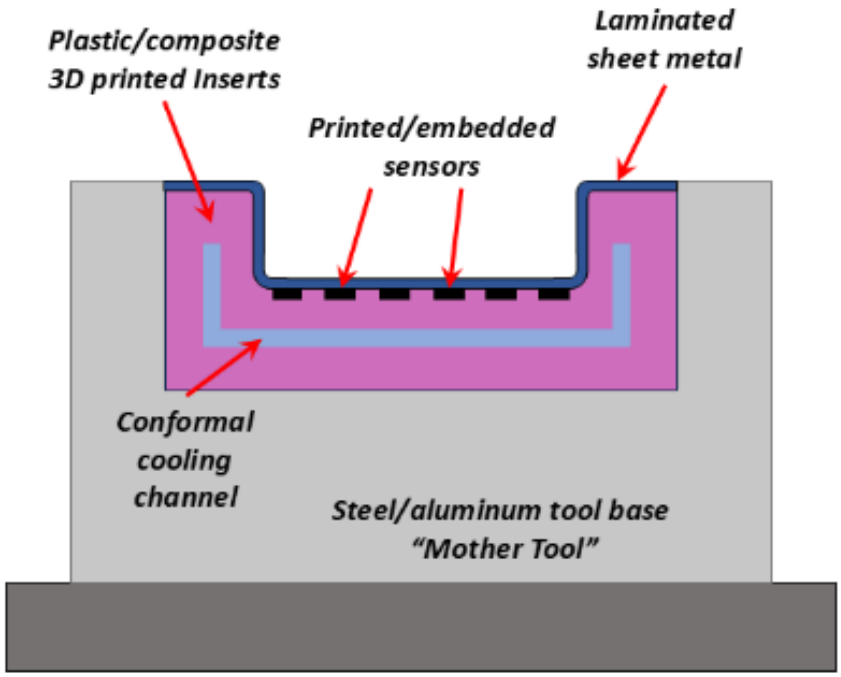

Figure 8: Schematic of the hybrid modular smart tooling

reducing operational interruptions promoting a more robust supply chain. These tactics highlight the HMT system's potential to meet the changing demands of contemporary industries by utilizing digital innovations and modular design principles, both of which can complement and improve the current manufacturing landscape.

6. Cost Benefit/Value Analysis

A rough cost estimation is provided to compare the manufacturing costs of tool inserts using the conventional method versus the proposed HMT method. In the traditional approach, a circular P20 steel raw material is selected, which is ground to achieve the required thickness and acceptable surface roughness. Following the sizing and grinding process, CNC milling creates the cavity shape. Based on rough estimates from local CNC shops, the total cost for two inserts—each corresponding to one side of the injection tool—is summarized in Table 3.

Table 3: Cost of making inserts with conventional methods

Raw material (Steel P20)	8 kg ($ 80/kg)	$ 640
Sizing and grinding	6 hours ($75 /h)	$ 450
CNC milling	18 hours ($ 100/h)	$ 1,800
Total		**$ 2,890**

The cost of manufacturing inserts using the novel HMT method is summarized in Table 4. The 3D printing process time for the inserts is calculated based on a 0.25 mm layer height, 60% infill, and a 50 mm/s printing speed. The laminated sheet material chosen is Aluminum 1100 with a thickness of 1 mm. The cost of the PIF process has not been included in this calculation.

Table 4: Cost of making inserts with the HMT approach

ABS filament	0.8 kg ($ 20/kg)	$ 16
Laminated sheet	0.14 kg ($ 35/kg)	$ 4.9
FDM time	32 hours ($ 15/h)	$ 480
Total		**$ 500.9**

Based on this cost analysis, manufacturing inserts for an injection molding tool using the HMT approach is approximately 82% cheaper than conventional methods. Furthermore, if recycled materials are used in the FDM process and incorporating a cement-plastic waste mixture in the HMT method is applied, costs could be reduced even further. This is because printing a shell structure for the insert would shorten the 3D printing process time, ultimately lowering the printing cost.

7. Conclusion

Combining the robustness and accuracy of conventional tooling methods with the quick prototyping and customization potential of additive manufacturing, the Hybrid Modular Tooling (HMT) system is a prime example of a significant advancement in manufacturing technology. In addition to increasing production flexibility and efficiency, this creative strategy establishes a new benchmark for sustainability in the tool manufacturing sector. Using recycled plastics to create 3D-printed polymer inserts and their integration with robust mother tools, the HMT system significantly minimizes material waste and maximizes the use of recycled materials. The system's modular design makes it simple to scale and customize. It enables fast adjustments to satisfy manufacturing requirements without the high expense and waste usually connected with conventional tool production. In addition to reducing the financial obstacles to advanced tooling, this strategy also lessens the environmental effect of tool manufacturing. The HMT system integrates with current digital and physical manufacturing infrastructures with real-time monitoring and embedded sensors. These features, which improve operational effectiveness and product quality through data analytics and flexible procedures, are aligned with Industry 4.0 standards.

In conclusion, the HMT system's innovative use of hybrid manufacturing techniques represents a transformative step forward, addressing both conventional tool-making's technical and environmental challenges. It offers a compelling example of how integrating

sustainable practices with cutting-edge technology can create economic value and advance the global manufacturing industry toward a more sustainable and efficient future. This system's development and implementation could serve as a blueprint for future innovations in various industrial sectors, promoting a wider adoption of sustainable manufacturing solutions.

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