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COMPARATIVE STUDY OF 3D PRINTING PIECES WITH FILAMENT AND POWDER

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ABSTRACT: This comparative study explores the impact of 3D printing technologies using filament and powder on dimensional accuracy, within the context of Industry 4.0 and rapid prototyping. In an era where efficiency and sustainability are essential, the analysis focuses on how these methods contribute to additive manufacturing processes, facilitating the rapid development of functional prototypes. The use of 3D scanners for precise measurements allows for the evaluation of part quality, highlighting the advantages of each technology in adapting to modern industrial requirements. The study emphasizes the importance of selecting the appropriate printing technology based on project specifications, thereby promoting not only innovation but also a reduced ecological impact through optimized material and resource utilization. This research contributes to a better understanding of the role of 3D printing in transforming industrial processes and supporting a circular economy

1. INTRODUCTION

The current industry faces multiple interconnected challenges: the need to shorten product development cycles, finding cost-effective solutions for small-series production, optimizing material consumption, rapidly adapting to continuously changing market demands, and implementing sustainable production processes. These aspects are compelling companies to rethink their production strategies and adopt new technologies and methods that allow them to remain competitive in a dynamic economic environment.

Additive Manufacturing (AM) represents one of the fundamental pillars of the Industrial Revolution 4.0, radically transforming traditional production paradigms. In the current context, where the demand for rapid prototyping and customized components is continuously growing, 3D printing technologies have become indispensable tools in the product development process.

The comparative study of FDM and SLS technologies highlights fundamental transformations in the context of Industry 4.0, demonstrating a significant evolution in how additive manufacturing integrates into the modern industrial ecosystem.

First and foremost, digital integration represents an essential aspect. Both technologies facilitate the creation of a complete digital workflow, starting from CAD modeling through to final manufacturing. Modern systems enable direct data transfer and continuous process monitoring through IoT sensor networks, ensuring complete traceability of each manufactured part.

Through these technologies, flexible manufacturing becomes a tangible reality. AM systems enable rapid adaptation to market demands, facilitating mass customization at competitive costs. This aspect supports the concept of decentralized production and on-demand manufacturing, fundamentally transforming traditional supply chains.

Last but not least, sustainability and efficiency aspects are optimized through precise monitoring of energy consumption and intelligent material management. Integration into the circular economy concept becomes more accessible through the ability to track and optimize resource utilization.

These transformations demonstrate that AM technologies are becoming essential components in the implementation of Industry 4.0. They offer an unprecedented level of control, flexibility, and efficiency in modern production processes, aspects that are also highlighted in recent scientific research.

Thus, paper [1] analyzes additive manufacturing technologies, focusing on fundamental processes and modern industrial applications. It presents the main 3D printing technologies: material extrusion (FDM), photopolymerization, selective laser sintering (SLS), and powder bed fusion. In the FDM-SLS comparison, differences in dimensional accuracy and mechanical properties are highlighted, with FDM offering accessibility and low costs, while SLS excels in precision and isotropic properties. Case studies from aerospace and medical industries demonstrate the versatility of these technologies, while the analysis of economic and sustainability aspects guides the optimal technology selection for each application.

Similarly, [2] presents a practical perspective on 3D printing technologies, with special emphasis on industrial design and implementation aspects. The authors provide a comprehensive guide for selecting the appropriate technology based on application, focusing on Design for Additive Manufacturing (DfAM) optimization. In the FDM-SLS comparison, the manual provides concrete data regarding achievable tolerances: FDM (±0.15 mm to ±0.5 mm) versus SLS (±0.1 mm to ±0.3 mm). Industrial case studies are presented demonstrating the advantages and limitations of each technology, including economic aspects and production considerations. Special attention is given to material selection and process parameter optimization for maximizing finished part quality.

In [3], a comprehensive analysis of additive manufacturing is conducted, focusing on composite materials and FDM and SLS technologies in the context of polymeric materials. The study highlights the evolution from conventional polymers to advanced composites, presenting comparative data where PLA/carbon fiber composites (FDM) achieve tensile strengths of 70 MPa, while PA12/glass fiber composites (SLS) demonstrate superior isotropic properties with strengths of 85 MPa. The identified challenges include optimization of material interfaces, process parameter control, anisotropy reduction, high costs, and the need for standardization, with the paper concluding with future research directions for advanced industrial application

Study [4] analyzes the mechanical properties of PLA components manufactured using FDM technology, focusing on the influence of infill density. Test specimens were produced at different infill densities (25%, 50%, 75%, and 100%), using optimal process parameters. Mechanical tests, conducted according to ASTM standards, included measurements of hardness, tensile strength, impact, and bending resistance. The results demonstrate that mechanical properties increase proportionally with infill density, with 100% density specimens exhibiting the best mechanical characteristics.

Based on a systematic analysis of 54 experimental studies, the paper [5] presents a comprehensive investigation of FDM process parameters' influence on the mechanical properties of 3D printed polymer parts. The research identifies extrusion temperature as the main factor, demonstrating that a controlled increase of 20°C can improve tensile strength by up to 30%, while print speed and layer height significantly influence surface quality and mechanical properties. The study highlights the importance of part orientation on anisotropy, showing that optimal orientation can double the tensile strength, and establishes an exponential relationship between infill density and elastic modulus. These results, along with practical recommendations for FDM process optimization, provide a solid scientific foundation for specialists in the field of additive manufacturing.

The review paper [6] analyzes recent developments in the 3D printing of polymer matrix composites, highlighting the interaction between reinforcement materials and polymer matrices. The study presents advances in composite filament development for FDM, demonstrating improvements in tensile strength of up to 200% through the incorporation of carbon and glass fibers, and analyzes the advantages of composite powders in SLS technology. The research emphasizes current challenges, such as fiber orientation control and homogeneous distribution of reinforcement material, and identifies future development directions, including smart composite materials and real-time monitoring technologies, with applications in the aerospace and medical fields.

The analysis of polymers used in laser sintering, from the perspective of the relationship between material properties and process parameters, with a focus on polyamides and high-performance polymers, is addressed in [7]. The research emphasizes the importance of the processing window, demonstrating that for PA12 this is approximately 30°C, and analyzes critical aspects such as temperature control and powder reusability (up to 50% in the mixture). The study concludes with an evaluation of trends in the development of new materials for LS, emphasizing the potential of high-performance polymers and the need for simultaneous optimization of powder properties and process parameters.

Research [8] focuses on the SLS process for polymeric materials, with special emphasis on PA12. The authors present a detailed analysis of the relationship between process parameters and final part properties. The study demonstrates that the optimal laser energy density for PA12 is between 0.1-0.13 J/mm³, resulting in relative densities >98% and superior mechanical properties (tensile strength ~48 MPa). The effects of powder particle size distribution and scanning strategies on dimensional accuracy and surface quality are analyzed. The paper highlights the importance of temperature control in the build chamber for minimizing deformations and optimizing mechanical properties.

The characteristics of polyamide powders in the laser sintering process are analyzed in [9]. A "processability index" is introduced based on differential thermal analysis and powder rheology. The study demonstrates that for PA12, a Hausner ratio below 1.25 and a repose angle below 45° are essential for optimal processing, while a minimum difference of 20°C between crystallization and melting temperatures ensures process stability. The research provides practical recommendations for powder selection and characterization, establishing a methodological framework for material evaluation.

Researchers [10] explore the fundamental principles of Design for Additive Manufacturing (DfAM), highlighting opportunities and constraints specific to FDM and SLS technologies. The authors present a methodological framework for design optimization, taking into account the specifics of each technology. For FDM, the importance of part orientation and support structures is emphasized, with specific recommendations for minimizing them. In the case of SLS, greater design freedom is highlighted, but with emphasis on thermal and post-processing considerations. The study includes practical design guidelines, such as minimum self-supporting angles (45° for FDM, 30° for SLS) and recommended minimum wall thicknesses.

Paper [11] analyzes the scientific and technological challenges in additive manufacturing, evaluating market opportunities and integrating technical and economic aspects. The main barriers to the industrial adoption of AM are identified, with an emphasis on polymer technologies, where microstructure control and property reproducibility remain critical. Market analysis indicates an annual growth of 25% until 2027, particularly in the aerospace, medical, and automotive sectors. The importance of standardization and opportunities in smart materials development, hybrid manufacturing, and Industry 4.0 integration are highlighted, emphasizing the need for a systematic approach to developing a robust industrial ecosystem.

Paper [12] analyzes polymers used in additive manufacturing, exploring the connection between chemical structure and performance in 3D printing. It highlights progress in material development for FDM and SLS, focusing on optimizing rheological and thermal properties. For FDM, new compositions that reduce anisotropy are presented, and for SLS, crystallization control strategies. Advanced materials with specific properties (shape memory, conductivity, self-healing) and sustainability aspects are addressed. The research emphasizes the importance of molecular design for the next generation of AM materials and the need to integrate green chemistry principles.

Study [13] analyzes the environmental impact of additive manufacturing technologies, comparing FDM and SLS from a sustainability perspective. The authors evaluate energy consumption, material usage, and recycling potential for both technologies. For FDM, average energy consumption is 0.5-1 kWh/hour, with the possibility of using biodegradable materials (PLA). SLS shows higher energy consumption (3-5 kWh/hour) but offers the advantage of partial reuse of unused powder. The study highlights the potential of additive manufacturing to reduce waste and optimize supply chains through local production.

The environmental implications of additive manufacturing, evaluating the ecological impact of various AM technologies in terms of energy consumption (50-400 kWh/kg material), emissions, and waste management are analyzed in [14]. The study highlights that, although AM is considered a "green" technology, the environmental impact varies significantly depending on technology and use. It emphasizes challenges related to VOC emissions and low recycling rates (20-30%), providing recommendations for reducing ecological footprint through energy optimization, development of biodegradable materials, and implementation of circular economy principles.

Report [15] provides a detailed analysis of the polymer additive manufacturing sector, projecting a compound annual growth (CAGR) of 17.8% until 2029. The study identifies three main growth sectors: automotive, medical, and consumer goods, which together represent 65% of the total market. In the technological domain, the report highlights the continued dominance of FDM (45% market share) and SLS (30%) but notes rapid growth in emerging technologies such as HSS (High-Speed Sintering). The materials market analysis indicates increasing demand for high-performance polymers, with PA12 and PEEK/PEKK representing 40% of total consumption. The study predicts a significant transformation in supply chains, with 35% of manufacturers planning to implement distributed production centers by 2027. A 25% reduction in production costs is anticipated by 2029.

The purpose of this article is to highlight the differences in dimensional accuracy, relative position, and form precision when using SLS and FDM additive manufacturing technologies.

2. METHODOLOGY

The test parts were made from PA12 polyamide. PA12 polyamide in filament form is a semi-crystalline thermoplastic polymer from the polyamide family, available for 3D printing as a filament with 1.75mm or 2.85 mm diameter, having a natural white-translucent color. This material stands out through its good impact resistance, low moisture absorption compared to PA6, high chemical resistance, excellent durability, and advantageous tribological properties. However, PA12 also presents some limitations, requiring drying before processing, being sensitive to moisture during storage, having a relatively high cost, and requiring high processing temperatures, as well as an enclosed chamber for optimal printing. Table 1 presents the main properties of PA12 polyamide [16], [17], [18], [19], [20], [21].

Table 1. Properties of Polyamide PA12

Category	Property	Value
Mechanical properties	Tensile strength	45-50 MPa
	Elastic modulus	1500-1800 MPa
	Elongation at break	200-300%
	Shore D hardness	75-80
Physical properties	Melting temperature	175-185°C
	Printing temperature	230-260°C
	Bed temperature	90-110°C
	Glass transition temperature	~40°C
	Density	930-1000 kg/m³
	Water absorption	0.66%
Processing conditions	Recommended drying	4-6 hours at 80°C
	Printing speed	30-60 mm/s

For producing the parts, a Flashforge Guider II fused deposition modeling (FDM) printer and a Formiga Velocis 110 Selective Laser Sintering printer were used.

The Flashforge Guider II is a professional 3D printer offering a generous print volume, equipped with a touchscreen and multiple connectivity options (USB, WiFi, and Ethernet). It features a heated bed benefits from assisted bed leveling technology, and includes functions such as filament detection and print resumption in case of interruption, making it suitable for both professional use and hobby purposes. The main characteristics are presented in Table 2.

The FORMIGA 3D printer manufactured by EOS features advanced characteristics in both software and process control, offering an intuitive operator interface and real-time monitoring capability of all critical parameters.

Table 2. Technical specifications of FlashForge Guider II.

Parameter	Specification
Technology	FDM (Fused Deposition Modeling)
Print Volume	250 x 280 x 300 mm
Layer Resolution	50-200 microni
Nozzle Diameter	0.4 mm
Filament Diameter	1.75 mm
Print Chamber	Closed
Maximum Bed Temperature	120°C
Maximum Nozzle Temperature	300°C
Maximum Print Speed	150 mm/s

Process data management and networking capabilities ensure perfect integration into the production workflow. The main characteristics are presented in Table 3

Table 3. Technical specifications of Formiga Velocis 110.

Parameter	Specification
Technology	SLS (Selective Laser Sintering)
Build volume	200 x 250 x 330 mm
Layer thickness	60-120 μm
Scanning speed	up to 5 m/s
Laser spot diameter	0.42 mm
Thermal control	Precise system for the build chamber
Control software	EOS RP Tools
Laser type	CO_2
Laser power	30W (Velocis), 40W (FDR)
Scanner	High precision F-theta
Layer application system	Dual rollers
Temperature control	Digital, real-time
Cooling system	Integrated

From a safety and environmental protection perspective, the system benefits from a closed processing architecture, with a nitrogen-controlled atmosphere, multiple integrated safety systems, and an advanced emission filtration system, thus ensuring both operator protection and minimization of environmental impact.

The 3D model of the part to be printed is presented in Figure 1. The 3D model is necessary both for 3D printing and for determining deviations in the measured parts, with the 3D model being considered the reference part.

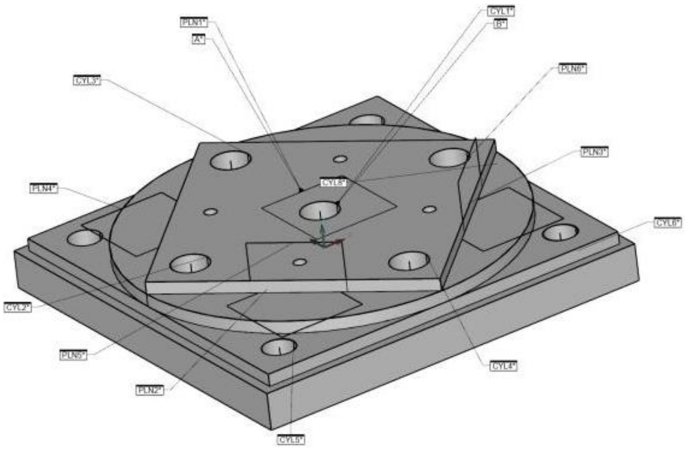

Figure 1. 3D model of the printed part.

Figure 2 shows the created entities (planes, cylinders) between which linear, angular, form, and position measurements are made.

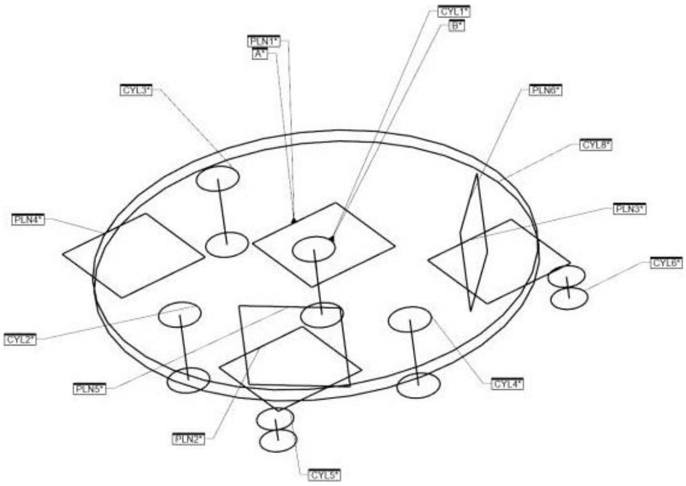

Figure 2. Entities used for measurements.

The part produced using filament printing technology (FDM) is presented in Figure 3.

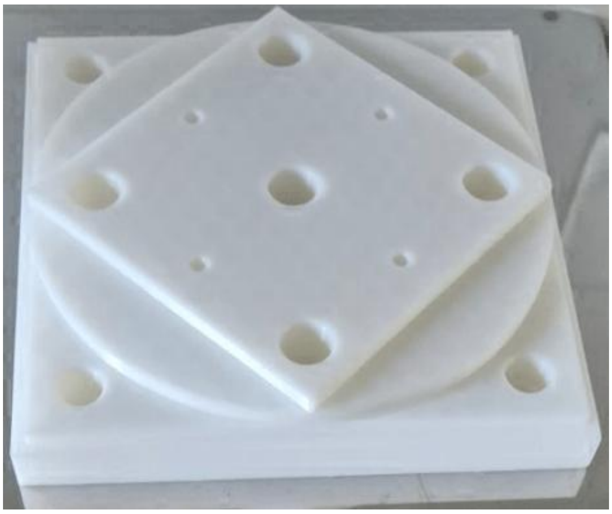

Figure 3. Part printed with FDM technology.

Figure 4 shows the part produced using SLS technology.

Figure 4. Part printed with SLS technology.

The scanning was performed using Hexagon's RS6 laser scanner. It distinguishes itself through its capability to generate detailed point clouds at high speeds while maintaining a high level of accuracy. SHINE technology optimizes the scanner's performance, enabling high-quality and precise measurements. Extended scanning width of 150 mm at medium operating range

High scanning speed with a frame rate of 300 Hz allows faster scanning without sacrificing point cloud details. These characteristics make the RS6 a valuable tool for applications requiring rapid and accurate 3D data capture.

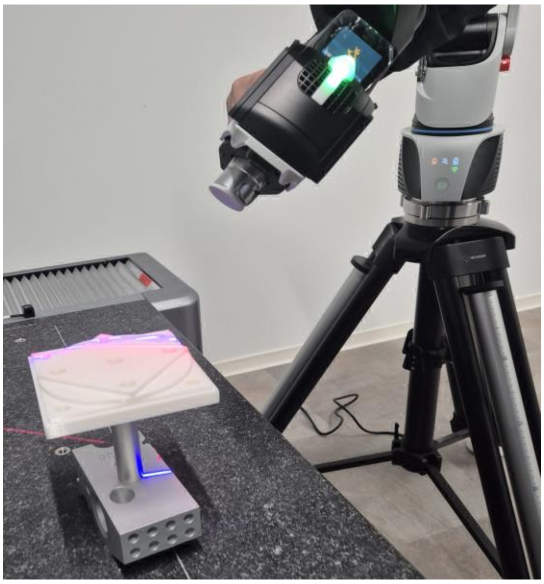

Figure 5. Scanning of 3D printed parts.

The scanner emits a laser beam or uses structured light technology to measure distances to the part's surface. These measurements are collected as 3D points. The raw data is processed to form a point cloud representing the part's surface. This point cloud is a collection of 3D coordinates. Data filtering and cleaning are performed by removing isolated points that are not part of the part's surface and applying smoothing algorithms to improve surface quality (Figure 6).

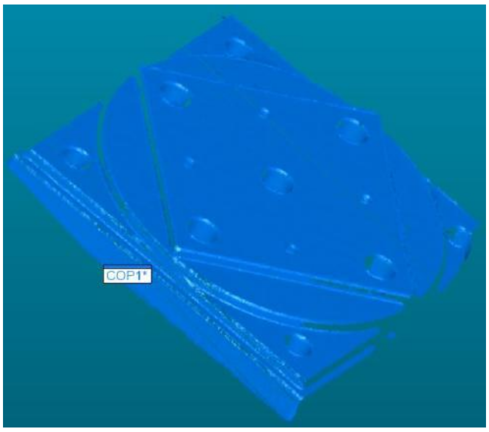

Figure 6. Point cloud acquisition and processing.

3. RESULTS AND DISCUSSIONS

The scanned data is used to verify the part's conformity with the specifications indicated in the execution documentation. The scanned 3D model is compared with the reference 3D CAD model to identify dimensional deviations. It can generate detailed reports.

Figure 7 shows the overlay of the CAD model with the point cloud of the part produced using FDM technology. Figure 8 shows the overlay with the point cloud of the part produced using SLS technology. The green area represents overlaps with the CAD model within the set range of ±0.05 mm.

Colours towards the red zone represent areas with positive deviations, while areas towards the blue zone represent negative deviations of the scanned point cloud compared to the CAD model. On these overlays, precise measurements of dimensions, angles, and other geometric characteristics of the part can be performed, and the analysis software highlights differences and generates detailed reports on demand. The measurements were performed in the same order for both parts.

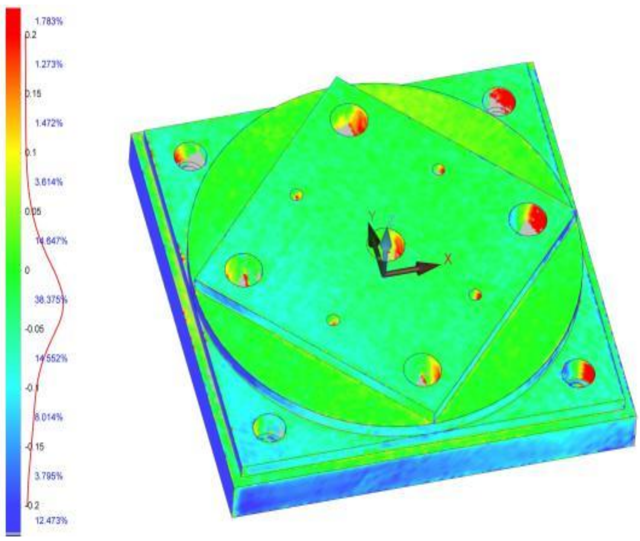

Figure 7. Point cloud of the part manufactured by FDM technology superimposed with the CAD model.

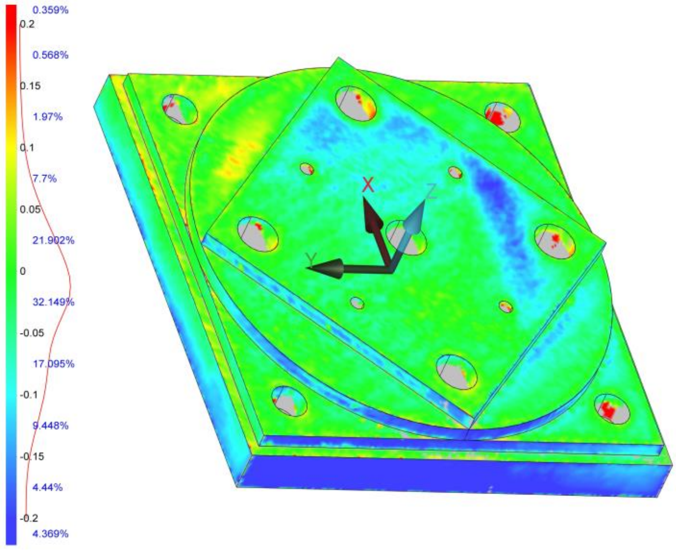

Figure 8. Point cloud of the part manufactured by SLS technology superimposed with the CAD model.

Figure 9 shows a capture from the measurement report showing how values are indicated on the verified entities. Table 4 presents a centralized summary of the measurements performed for the part produced using FDM technology.

Table 4. Measurement results for the part manufactured by FDM

FEAT	ID	MEAS	NOM.	DEV.
CYL1T0CYL2	DISTI	40.081	40.25	-0.169
CYL1 TO CYL4	DIST2	40.44	40.25	0.19
CYL2 TO CYL4	DIST3	80.68	80.5	0.18
CYL6TOCYL1	DIST4	43.912	43.75	0.162
CYL3TOCYL5	DIST5	80.574	80.5	0.074
PLN6 TO PLN7	ANGLI	90.332	90	0.332
PLN8 TO PLN9	ANGL2	90.219	90	0.219
PLN6	FCFPERP1	0.813	0	0.813
PLN7	FCFPERP2	0.821	0	0.821
PLN8	FCFPERP3	0.387	0	0.387
PLN9	FCFPERP4	0.889	0	0.889
CYL1	FCFCYLY1	0.821	0	0.821
CYL2	FCFCYLY2	0.723	0	0.723
CYL6	FCFCYLY3	0.787	0	0.787
CYL8	FCFCONCEN1	0.711	0	0.711

Tables 4 and 5 present a centralized summary of the measurement results for the parts manufactured using FDM and SLS technologies respectively. The evaluation of the two printing technologies was done by comparing deviations for each category of measurements performed

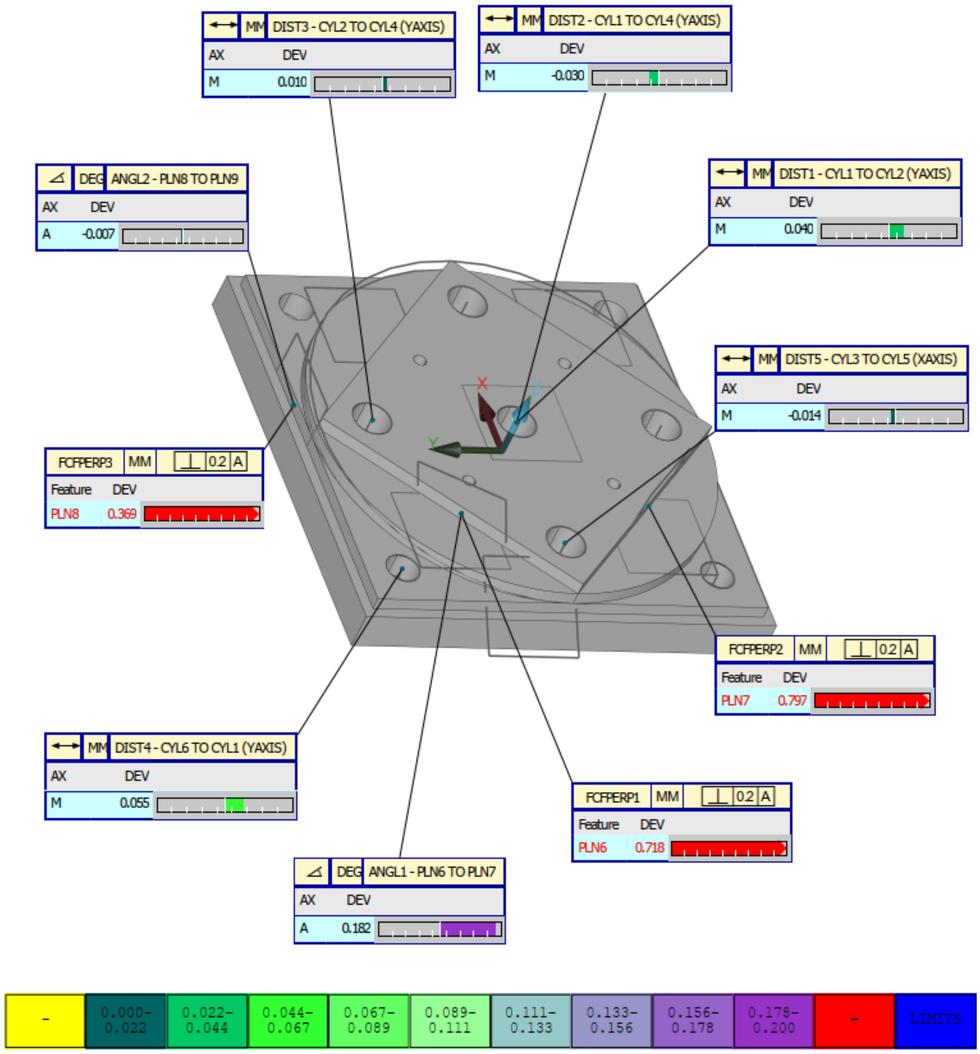

Figure 9. Indication of measured values.

Table 5. Measurement results for the part manufactured by SLS

FEAT	ID	MEAS	NOM.	DEV.
CYL1T0CYL2	DISTI	40.29	40.25	0.04
CYL1 TO CYL4	DIST2	40.22	40.25	-0.03
CYL2 TO CYL4	DIST3	80.51	80.5	0.01
CYL6TOCYL1	DIST4	43.805	43.75	0.055
CYL3TOCYL5	DIST5	80.486	80.5	-0.014
PLN6 TO PLN7	ANGLI	90.182	90	0.182
PLN8 TO PLN9	ANGL2	89.993	90	-0.007
PLN6	FCFPERP1	0.718	0	0.718
PLN7	FCFPERP2	0.797	0	0.797
PLN8	FCFPERP3	0.369	0	0.369
PLN9	FCFPERP4	0.858	0	0.858
CYL1	FCFCYLY1	0.712	0	0.712
CYL2	FCFCYLY2	0.695	0	0.695
CYL6	FCFCYLY3	0.729	0	0.729
CYL8	FCFCONCEN1	0.647	0	0.647

As shown in Tables 4 and 5, measurements were made for distances, angles, perpendicularity, cylindricity, and concentricity. For a quick understanding of the differences between the two technologies, the deviations resulting from measurements against nominal values were graphically represented for each category of determinations. Figure 10 shows the deviation of the distance between the hole axes for the two printing technologies.

Figure 10. Distance deviation between hole axes.

Figure 11 presents the comparison of angular deviation for the two printing technologies.

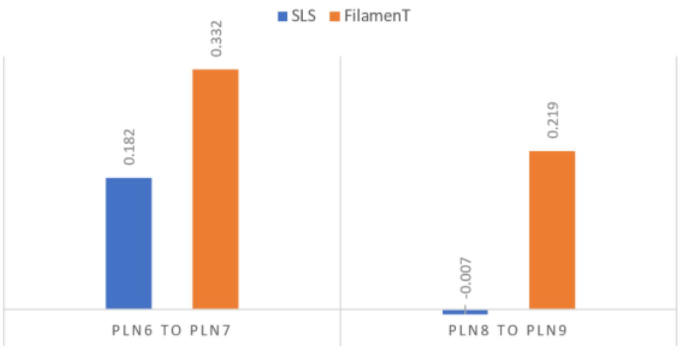

Figure 11. Comparison of angular deviation.

Figure 12 presents the comparison of perpendicularity deviation for the two printing technologies.

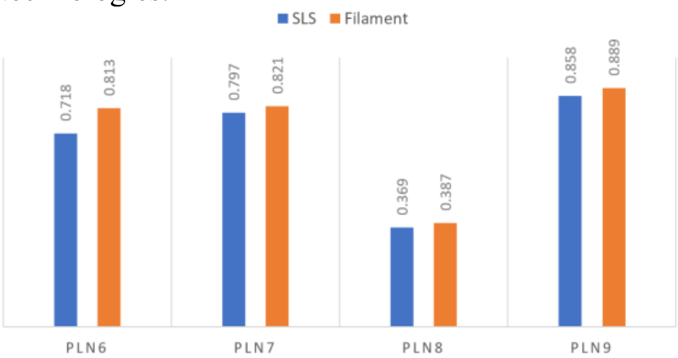

Figure 12. Comparison of perpendicularity deviation.

Figure 13 presents the comparison of cylindricity deviation for the two printing technologies.

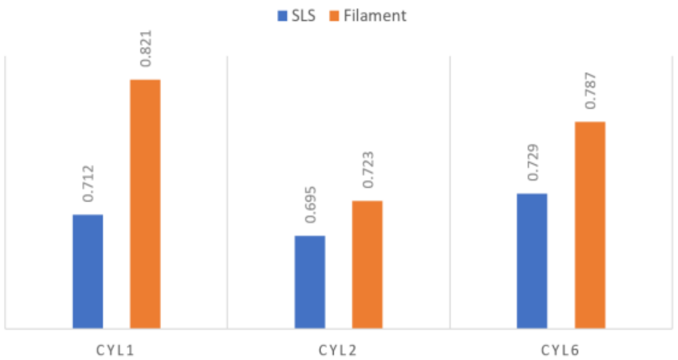

Figure 13. Comparison of cylindricity deviation.

Figure 14 presents the comparison of concentricity deviation for the two printing technologies.

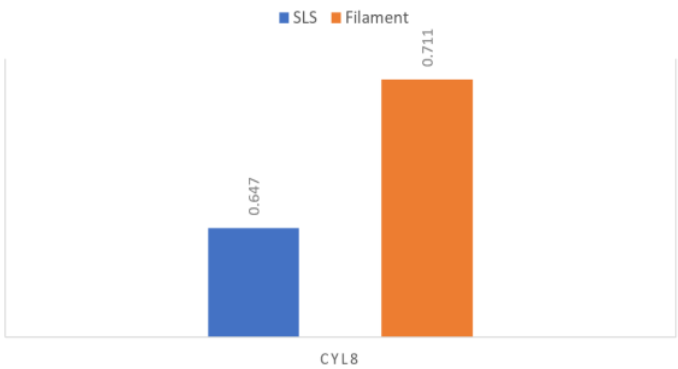

Figure 14. Comparison of concentricity deviation.

4. CONCLUSIONS

Additive manufacturing represents a fundamental pillar in the digital transformation of modern industry, marking a crucial stage in the evolution of production processes. In the context of Industry 4.0, this revolutionary technology redefines traditional manufacturing paradigms, offering innovative solutions for contemporary challenges in industrial production. The convergence between digital technologies and additive manufacturing processes opens new horizons in product development and optimization, enabling unprecedented flexibility and customization.

Additive manufacturing technologies, particularly Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) represent two distinct but complementary approaches in the modern manufacturing ecosystem. This technological duality addresses a broad spectrum of industrial requirements, from conceptual prototyping to the production of functional components.

In this context, the comparative analysis of dimensional accuracy between FDM and SLS technologies becomes essential for optimizing production processes and ensuring finished product quality. The systematic evaluation of dimensional tolerances, form accuracy, and position provides important data for selecting the optimal technology based on specific application requirements. This methodical approach in the comparative study of additive technologies contributes to the development of more efficient and sustainable production practices, aligned with Industry 4.0 objectives.

The comparative analysis of dimensional deviations between additive manufacturing technologies reveals significantly superior precision of the SLS process, with deviations between -0.03 mm and +0.055 mm, compared to FDM technology which shows considerably larger deviations, between -0.169 mm and +0.19 mm. This approximately 5-fold difference in dimensional accuracy demonstrates that SLS represents the better option for applications with high accuracy requirements, while the use of FDM may require dimensional compensations during the design phase.

The analysis of angular deviations between the two additive manufacturing technologies highlights notable differences in their ability to maintain geometric precision. SLS technology demonstrates superior performance, with moderate to negligible angular deviations, indicating precise geometry control. In contrast, FDM technology shows consistently larger angular deviations, suggesting an inherent process limitation in maintaining angular precision. This performance difference, corroborated with the previous results of dimensional deviations, reinforces the position of SLS technology as being more suitable for applications requiring high geometric precision.

When analyzing the perpendicularity of surfaces relative to reference "A", it is observed that while both processes show deviations from ideal perpendicularity, SLS technology consistently demonstrates lower deviation values across all measured surfaces. This difference maintains the general trend of SLS technology's superior precision. It is important to note that the differences between the two technologies are less pronounced in terms of perpendicularity, suggesting that this geometric parameter might be influenced by factors common to both processes, such as part orientation during manufacturing or gravitational effects. For applications where surface perpendicularity is critical, both technologies might require additional process optimization strategies or compensations during the design phase.

The cylindricity analysis highlights the superiority of SLS technology in maintaining the precision of cylindrical forms, showing consistently lower deviations compared to FDM technology. This difference can be attributed to the nature of the sintering process, which provides a more uniform construction, in contrast to the layering effect specific to FDM technology. The results confirm the advantage of SLS for applications requiring high geometric precision of cylindrical surfaces.

Concentricity measurements confirm the trend previously observed in other geometric analyses. SLS technology maintains an advantage in geometric precision, demonstrating lower deviation from ideal concentricity compared to the FDM process. This difference supports the general conclusion that SLS offers superior control of complex geometric characteristics.

Following the complete comparative analysis of the two additive manufacturing technologies, SLS and FDM, the results consistently demonstrate the superiority of the SLS process in all measured geometric aspects. SLS technology shows significantly smaller deviations, on average 30-50% lower than the FDM process, highlighting superior dimensional and geometric precision. This marked difference recommends SLS technology for applications requiring tight tolerances and high geometric accuracy, while FDM technology may require dimensional and geometric compensations during the design phase to achieve desired specifications.

5. ACKNOWLEDGEMENTS

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