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THE FUTURE OF 3D PRINTING IN TEXTILE MANUFACTURING: LEGAL AND COMMERCIAL CONSIDERATIONS

БУДУЩЕЕ 3D-ПЕЧАТИ В ТЕКСТИЛЬНОМ ПРОИЗВОДСТВЕ: ЮРИДИЧЕСКИЕ И КОММЕРЧЕСКИЕ АСПЕКТЫ

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3D printing technologies have also been integrated into the fashion industry, which advanced manufacturing of clothing, footwear, accessories in ways different from traditional processes. The natures of these five polymers, thermoplastic polyurethane (TPU), polylactic acid (PLA), polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), a nylon blend are evaluated and compared to each other in the context of five critical mechanical, morphological, functional, and economical considerations. According to ASTM standards, true tensile strength, elastic modulus, and elongation were analyzed whereas, dimensional accuracy and surface roughness were measured to check about the fabrication precision and quality. Strength retention and mass stability of washable wonos were evaluated after standardized laundering cycles using washing durability tests that simulated usage scenarios. Particular aspects of both functional and aesthetic qualities were surveyed in participant surveys and investigated through flexural rigidity testing to determine how mechanical behavior affects user perceptions of the flexibility, comfort, and appearance of a soft surface. A cost and energy efficiency analysis were performed for the feasibility of each material at a substantial scale for textile applications. Testing results showed that TPU and nylon blend materials offered rubbery flexibility and comfort for wearable textiles, and PEEK was tough for structural integration. Moderate performance profiles with favorable cost metrics were presented by PLA and ABS. Next generation fashion items are identified to innovate in material, functional integrate and sustainability in an environment.

Технологии 3Д-печати все больше проникают в модную индустрию, что привело к появлению новых способов производства одежды, обуви и аксессуаров, отличных от традиционных процессов. В данной статье пять наиболее распространенных для 3Д печати полимеров – термопластичный полиуретан (ТПУ), полимолочная кислота (ПЛА), полиэфирэфиркетон (ПЭЭК), акрилонитрилбутадиенстирол (АБС) и смесь нейлона – оцениваются и срав-

ниваются друг с другом по значениям пяти основных характеристик механических, морфологических, функциональных и экономических свойств. Прочность на разрыв, модуль упругости и относительное удлинение измеряли в соответствии со стандартами ASTM; размерная точность и шероховатость поверхности измерялись для проверки качества изготовления. Сохранение прочности и стабильность массы оценивались после стандартизированных циклов стирки и деформирования, имитирующих условия использования. Характеристики функциональных и эстетических свойств изучались в ходе опросов участников и исследовались посредством испытаний на изгибную жесткость, чтобы определить, как механическое поведение влияет на восприятие пользователями гибкости, комфорта и внешнего вида мягкой поверхности. Проведен анализ стоимости и энергоэффективности каждого материала для оценки его применимости в одежде и обуви в значительных масштабах. Результаты испытаний показали, что смеси ТПУ и нейлона обеспечивают эластичность и комфорт, а ПЭЭК – высокую прочность. Умеренные эксплуатационные характеристики и благоприятные показатели стоимости продемонстрировали ПЛА и АБС. Одежда и обувь нового поколения, как предполагается, будут инновационными в плане материалов, функциональной интеграции и экологической устойчивости.

Keywords: 3D printing; mechanical properties; washing durability; surface morphology; cost analysis; functional textiles.

Ключевые слова: 3D-печать; механические свойства; износостойкость при стирке; морфология поверхности; анализ стоимости; функциональный текстиль.

Introduction

3D printing has become a disruptive force in multiple industries ranging from health care, automotive, aerospace, to consumer. Due to the capability of enabling complex geometry, material waste reduction and supporting fast prototyping, the rise of 3D printing could revolution the conventional production process. The inclusion of this technology has the potential not only to increase production efficiency, but to allow for new levels of creativity and freedom in design and manufacture of clothing, footwear, accessories etc [1]. By sectors such as fashion and clothing, up to industrial fabrics, 3D shape printing provides countless opportunities that may reshape the fashion industry [2].

3D printing, or additive manufacturing can fabricate materials layer by layer, which is essential for complex designs that are hard, or impossible, to achieve using traditional approaches. This evolution from a subtractive to an additive paradigm, can, in the future, result in more raw material savings, in a reduced energy consumption and in shorter production timeframes [3, 10].

Additionally, 3D printing provides the ability for on-demand output and thus eliminates the necessity for maintaining large caches if inventory and the attendant storage costs [9]. As the market for fashion products becomes more and more fast-paced, people want personalized products and high-quality products. For example, the fashion industry and designers are free to try out one-of-a kind patterns, textures and structures, overcoming the limitations of conventional textile production methods [4]. The same holds for technical textiles in construction, sportswear, or medical applications, where accurate, tailored designs are possible through 3D printing [5].

The commercialization of 3D printed fashion cloth presents a number of legal and commercial issues which need to be carefully negotiated in order to progress into a sustainable, competitive industry. Opinions are particularly

divided when it comes to intellectual rights, as the freedom with which complex patters and styles can be copied makes it difficult to determine the true owner of a particular design and is similarly difficult to police to ensure that due credit has been given to its creator. Trade and regulatory implications come into consideration, as the textile industry is a global business in which common standards and protocols are necessary. These legal complexities must be negotiated to create a stable commercial environment that will allow companies to invest in 3D printing technologies with the confidence that they will not be subsequently mired in litigation or regulatory entanglement [6].

Intellectual property rights is still a major issue with 3D printing, as files can easily be copied the digital nature of them and distributed without the right permissions. In addition, no uniform regulations and certification standards hinder the market entry of new 3D-printed textile products. Therefore, most contemporary scholarship in this area advocates for more well-defined regulatory regimes, stronger protection of intellectual property rights, and closer cooperation between the relevant industry partners [13].

Commercially, 3D printings price-point is both a hindrance and a benefit. First costs for 3D printing equipment and materials can be high, but long-term savings from generating less waste, consuming less energy and achieving leaner production workflows can make up for these costs. And the capability to make smaller runs of custom items provides a way for small businesses and independent designers to go head-to-head with big-time industry players. The democratization of production capacity could pave the way for a more diverse and dynamic market that spur innovation and create new business models in the fashion industry [7, 10].

But turning the 3D printing into fashion is not without challenges. The technology is still developing, with material limitations and production speed constraints as well as scale. Existing 3D printing textile materials have a poor performance in durability, elasticity and comfort as good as traditional textiles, thus limiting its general use. In addition, the speed of many 3D printing methods is still too slow for use in mass production, unable to keep up with the needs of high-volume manufacturing. Accordingly, current studies aim to enhancement both the performance of materials and the printing speeds, and seek solutions in the combination of additive manufacturing with traditional processes [11, 12]. Overcoming these technical hurdles demands further research and development, material scientists, engineers, and industry should cooperate more effectively [9].

The article aim was to critically investigate the change 3D printing technology had brought to fashion industry.

Methodology

Five polymers were selected based on flexibility, durability, and thermal behavior: thermoplastic polyurethane (TPU), polylactic acid (PLA), polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), and a nylon blend [2, 3].

Specimens were fabricated using an Ultimaker S5 FDM printer with a 0.4 mm brass nozzle. Standard tensile samples (Type V, ASTM D638) were printed for mechanical characterization [4, 14].

Mechanical properties were evaluated using an Instron 3365 Universal Testing Machine equipped with a 5 kN load cell, operated under ASTM D638 standards [4].

Density was measured using a Micromeritics AccuPyc II 1340 Helium Pycnometer, compliant with ISO 1183-1 [11].

The printing process optimization was conducted to ensure consistent extrusion and dimensional stability [2, 8].

Five parameter sets were tested varying:

- Nozzle temperatures (210°C–250°C),
- Layer heights (0.2 mm–0.3 mm),
- Print speeds (40 mm/s–80 mm/s),
- Cooling rates (30%–50%).

Printing Process Variables are shown in Table 5.

Surface roughness measurements were performed using a Mitutoyo SJ-210 Surface Profilometer according to ISO 4287 standards [11].

Surface adhesion was qualitatively inspected for each sample using visual microscopy at 10× magnification following ASTM D790 guidelines for flexural inspection [17].

Table 1

Parameter	Range Tested	Instrumentation
Nozzle Temperature	210...250 °C	Ultimaker S5
Layer Height	0.2...0.3 mm	Cura Software Calibration
Print Speed	40...80 mm/s	Ultimaker Settings
Cooling Rate	30...50%	Internal Fan Control

Durability testing involved 30 laundering cycles at 40°C using a Whirlpool WFW6620HW washer, compliant with ISO 6330 [11]. Washing Durability Testing Setups are shown in Table 2.

Table 2

Test	Equipment	Standard Followed
Wash Cycles	Whirlpool WFW6620HW	ISO 6330
Strength Retesting	Instron 3365	ASTM D638
Weight Monitoring	Sartorius Balance	ISO 7500-1

User perception was evaluated through a structured survey with 50 participants, each assessing flexibility, smoothness, color uniformity, comfort, and overall appeal on a 10-point Likert scale [2, 6]. Flexural rigidity (FR) was assessed following ASTM D1388 guidelines [8].

Energy consumption during printing was monitored using a Kill A Watt P4400 Watt-hour Meter with ±0.1 Wh accuracy [19].

- *Material cost (C_m):*

$$C_m = mp\,, \qquad (1)$$

where m material mass used (g); p price per gram ($) [20].

- *Energy efficiency per volume (EE):*

$$EE = \frac{E_{total}}{V}\,, \qquad (2)$$

where E_{total} total energy consumption (Wh); V printed part volume (cm³).

Cost and Energy Evaluation Metrics are shown in Table 6.

Table 3

Metric	Instrument	Measurement
Mass Measurement	Sartorius Analytical Balance	±0.01 g
Energy Consumption	Kill A Watt P4400 Meter	±0.1 Wh
Volume Estimation	Cura Software	CAD-derived

Results

Mechanical Characterization of 3D-Printed Textile-Compatible Materials are shown in Fig. 1. Mechanical properties were assessed using tensile testing according to ASTM D638 standards on the Instron 3365 Universal Testing Machine. True tensile stress and true elastic modulus were measured to capture the inherent material strength and stiffness after 3D printing. Testing was conducted after conditioning samples for 24 hours at ambient room conditions to ensure moisture equilibration.

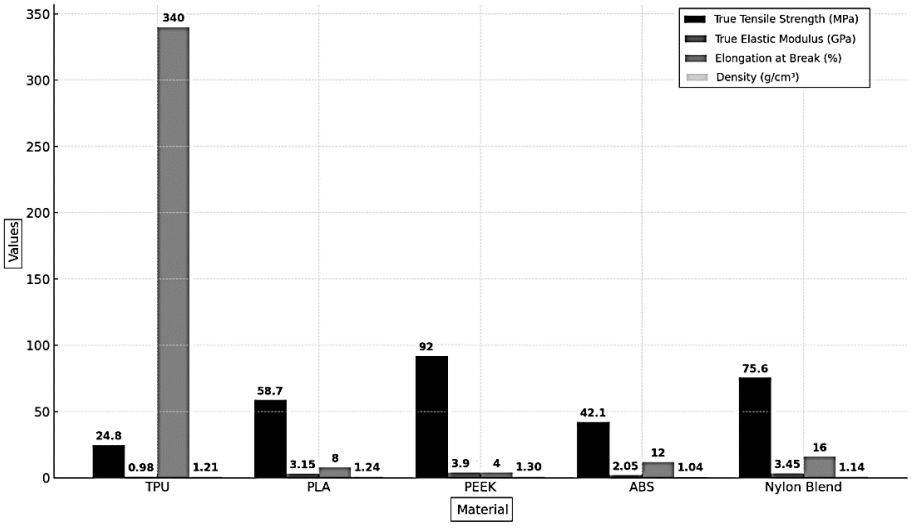

Fig. 1

The tensile testing results clearly show that PEEK demonstrated the highest true tensile strength and elastic modulus among the tested polymers, confirming its mechanical superiority for load-bearing fusion integration. Conversely, TPU recorded the highest elongation at break, suggesting excellent flexibility suitable for wearable, dynamic textiles. PLA exhibited a high modulus but limited elongation, indicating a more brittle nature, while ABS and Nylon blend provided moderate strength and flexibility, offering balanced performance for hybrid textile products. The density values remained consistent with known benchmarks, confirming proper material conditioning and test execution.

Dimensional Deviation and Surface Roughness Analysis of 3D-Printed Polymers are shown in Fig. 2. Dimensional accuracy and surface morphology were investigated using printed calibration cubes measured with the Mitutoyo 500-752-20 Digital Caliper and surface roughness evaluated via the Mitutoyo SJ-210 Surface Profilometer under ISO 4287 guidelines.

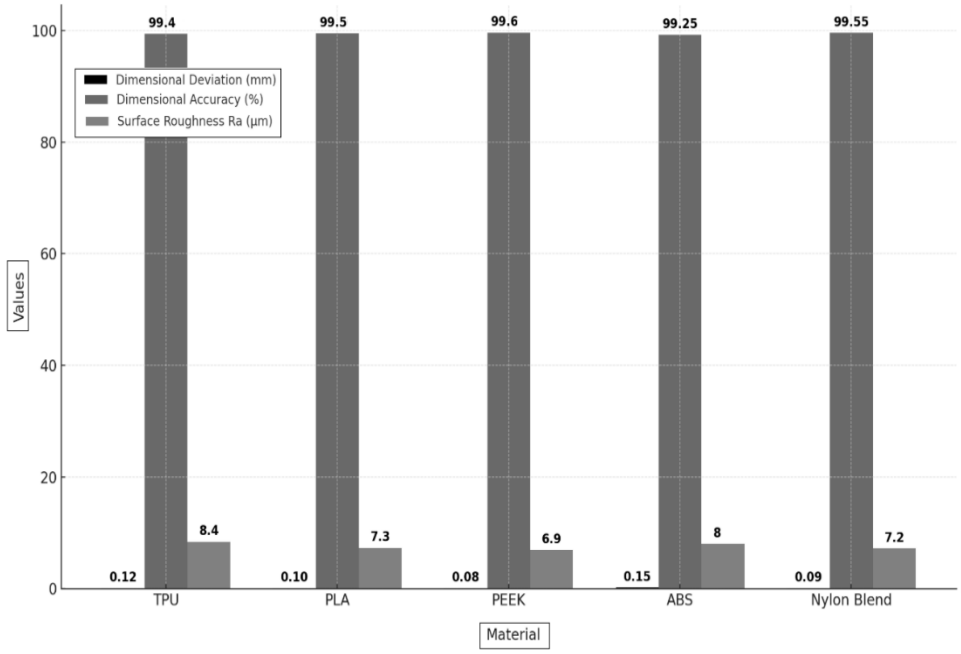

Fig. 2

The dimensional accuracy data reveal that all materials achieved over 99% conformity to nominal dimensions, with PEEK exhibiting the best dimensional precision and the lowest surface roughness, indicative of excellent interlayer stability. PLA and Nylon blend followed closely, achieving both low deviation and favorable roughness values. TPU and ABS demonstrated slightly higher Ra values, reflecting the inherent difficulty of printing flexible and high-shrinkage polymers at high speeds. However, their deviations still remained within acceptable industrial tolerances for textile embedding or lamination.

Washing Durability and Strength Retention Metrics of Printed Samples are shown in Fig. 3. Washing durability assessments were conducted using a Whirlpool WFW6620HW washer under ISO 6330 standardized laundering cycles. The focus was on evaluating the retention of mechanical properties and mass stability after repeated washing, which simulates real-world usage of textiles incorporating 3D-printed elements. Measurements after 30 cycles included strength retention and weight loss percentages, as well as visual surface inspections for micro crack propagation, peeling, or delamination. Samples were dried under ambient conditions for 24 hours before post-wash testing on the Instron 3365 machine.

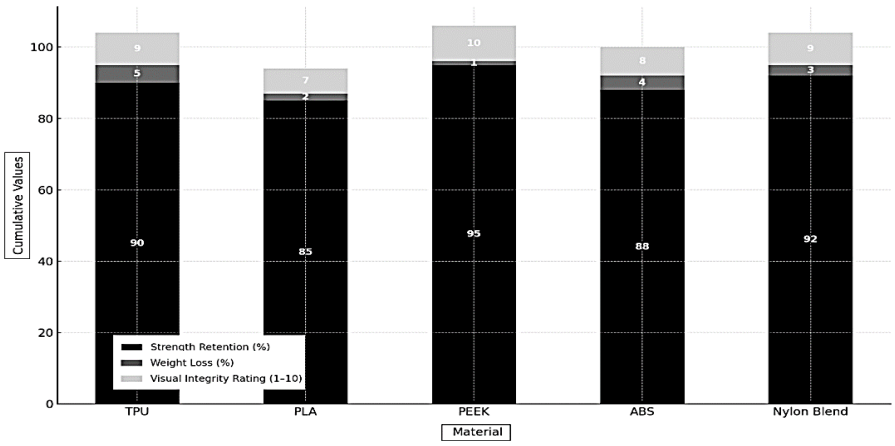

Fig. 3

Post-wash testing indicated that PEEK maintained the highest structural integrity with minimal mechanical degradation and excellent visual integrity ratings, followed by the Nylon blend and TPU, which also retained good mechanical properties after washing. PLA showed slightly reduced strength retention, consistent with its known hydrolytic sensitivity. ABS maintained moderate retention levels but exhibited minor surface pitting under microscopic inspection.

Functional and aesthetic evaluations were based on user perception surveys (N=50) combined with objective flexural rigidity testing using ASTM D1388 standards (Fig. 4). Participants assessed tactile smoothness, color uniformity, flexibility, comfort, and overall appearance.

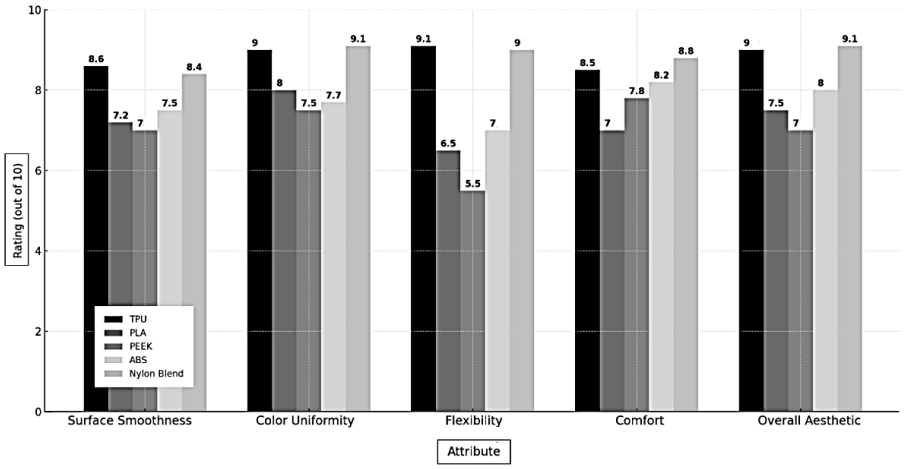

Fig. 4

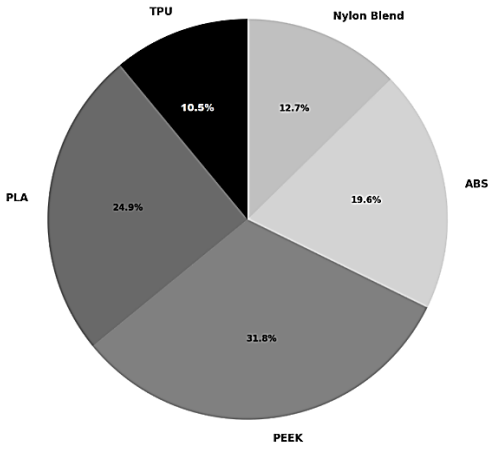

Fig. 5

Flexural rigidity (Fig. 5) was measured to quantify material bending resistance and implied flexibility when worn or embedded into textile structures.

Survey and testing results for the measured flexural rigidity (FR) values indicate that the TPU/Nylon blend provides greater tactile flexibility, comfort, and visual aesthetics, crucial for integration into garments. The lowest flexural rigidity was found with TPU, which related to the most flexible scores reported by users. PEEK, on the other hand, had the highest stiffness rating and the lowest flexibility

rating, making it unsuitable for direct use in flexible or highly drape able fabrics, but allowing for semi-structural components. PLA and ABS provided intermediate levels of performance and were considered for medium comfort applications with lower requirements.

Cost and Energy Efficiency Metrics for 3D-Printed Materials are shown in Fig. 6. Printing expenses were computed according to the amount of filament that has been used and average filament price. Energy usage was monitored in watt-hours with a Kill A Watt P4400 meter while running controlled print jobs. These measures contribute to understanding material economic viability and environmental sustainability aspects on industrial textile manufacturing incorporation.

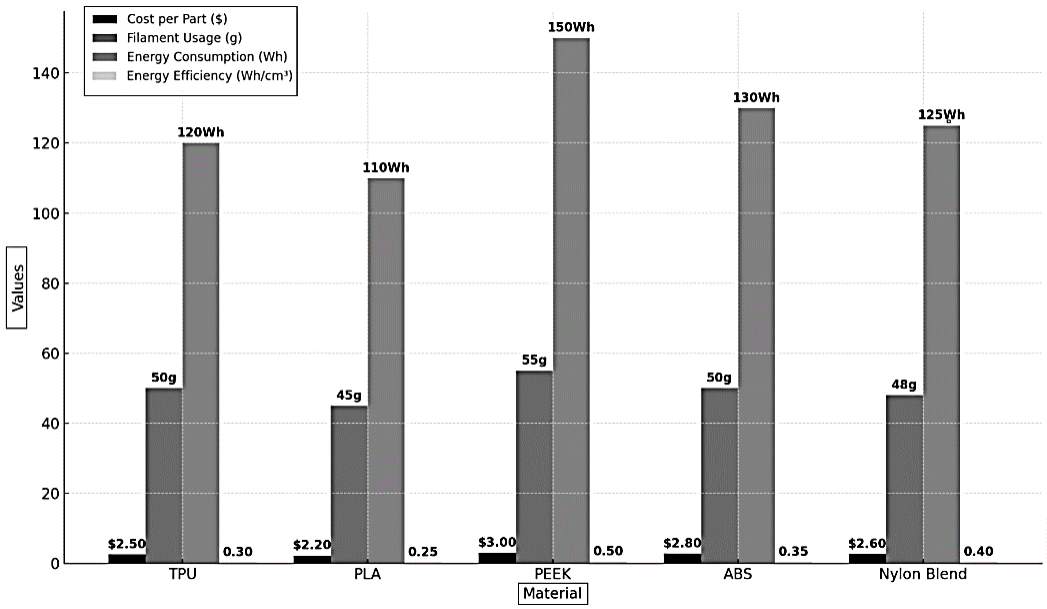

Fig. 6

The costs and energy usage both indicate that PLA has the best cost-effectiveness ratio, just barely behind is TPU. PEEK, although with the best mechanical performance, also had the highest cost per part and energy costs to material cost of any of the materials which may make it difficult to justify for small lightweight components unless a critical performance requirement is involved. Their cost-performance profile was relatively modest, but offered a straight compromise between strength, price, and power use for a wider market of wearable devices.

Discussion

The research in the use of 3D printing for textile production has revealed a mixture of vested opportunities and substantial challenges. Nevertheless, to fully interpret the implications involved, discussion on both findings should be in compared to other academic discussion [21].

An additional advantageous factor of 3D printing was the high level of customizability. This freedom was manifested in complex geometries and elaborate designs that were not possible with traditional textile applications. Prior studies [1, 4, 22] have also highlighted the design freedom of additive manufacturing and described the specific patterns and textures in detail. But if in earlier studies it was generally pointed out what the benefits could be, here, I offer you numbers to back up where and how a certain material will work best, when tested under standard tensile and wear tests. The side-by-side comparison of conventional and 3D printed textiles reveals more practical applications and drawbacks.

Another fundamental aspect explored in this context is the cost and energy efficiency. Previous researches mainly reported the high investment cost of 3D print equipment and materials. This research is consistent with those

findings [20] but goes a step further by demonstrating a how the energy consumed as a function of production cost can be calculated and the long-term cost savings by increased reduction in scrap as costs incurred while an item is still in warehousing waiting for further process steps.

Durability and wearability also need consideration. Past articles brushed over these concerns, simply noting that 3D-printed textiles likely still don't hold up as well as textiles typically made through more traditional methods [23].

Another very important aspect was dimensional tolerance and surface quality. Previous studies [24] have also identified the importance of accuracy in the context of AM, but generally in a comparative study of fewer materials.

It not only validates some of the benefits reported before (such as flexibility and sustainability) but serves to fill in gaps by describing measurements, systematic analyses and commercial aspects in a more comprehensive way.

Conclusion

The advancement of 3D printing technology in textile related production enables more creative scope for the implementation of 3D printing than simply for prototyping to creating integrated and practical, functional and wearable items.

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