Journal of Fundamental and Applied Research **Vol. 5**, Issue 1 (2025) **20250005**

Received: 19 February 2025 / Accepted: 27 March 2025
Published online: 27 March 2025
© 2025 The Author(s)

STRENGTH ENHANCEMENT OF 3D-PRINTED COMPONENTS

Alexander Rogachev,[1] Bobirjon Adizov,[2] Nasiba Bayrayeva,[2] Alisher Auyesbayev,[2] and Sayyora Ganieva[2]

[1]*Institute of New Materials Chemistry of the National Academy of Sciences of Belarus*
[2]*Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan*

Abstract: This article explores key methods for enhancing the strength of components manufactured using 3D printing technologies. The relevance of the topic stems from the growing demand for functional parts capable of withstanding various mechanical loads. Special attention is given to the selection of high-performance materials, including reinforced polymers and metals. Parameters such as tensile strength, flexural strength, impact toughness, Young's modulus, and elongation at break are analyzed. Comparative data on the properties of various materials, including polymers reinforced with carbon or Kevlar fibers, are provided. Practical aspects of improving the strength of 3D-printed parts are discussed, including optimization of print settings, model orientation, infill density, and thermal post-processing (particularly annealing). The article concludes that material selection should be guided by the nature of expected loads, and offers recommendations for designing structurally robust components. The findings may be useful in the development of durable and reliable parts in the field of additive manufacturing.

Keywords: Strength, mechanical properties, reinforced polymers, 3D printing, annealing, Young's modulus, impact toughness.

I. INTRODUCTION

In many cases, 3D printing requires the production of parts capable of withstanding significant mechanical loads. These loads are often complex and demand precise stress analysis at various points within a component. This article examines the key methods for increasing the strength of 3D-printed parts, including the selection of high-strength materials, optimization of print orientation, adjustment of infill density, post-processing techniques, and local reinforcement of the structure.

One of the most critical steps is selecting a material with reliable mechanical properties. Some high-performance materials are difficult to use in non-industrial settings due to their demanding printing temperature requirements. However, specialized services are available that can handle such materials. Commonly used strong plastics include ABS, PETG, ASA, and nylon [1].

It is important to distinguish between strength and stiffness. Some materials may exhibit high strength while remaining flexible (i.e., having a low Young's modulus) and prone to deformation under load. Others may be highly rigid but have low resistance to fracture. Additional important mechanical properties include compressive strength, flexural strength, impact toughness, and hardness.

In the context of tensile loading, two parameters are particularly important: ultimate tensile strength (UTS)—the maximum stress the material can withstand before breaking—and yield strength, which indicates the point at which permanent deformation begins, even if the material has not yet failed [1, 2].

II. ULTIMATE TENSILE STRENGTH OF METALS

1. Vibenite 290 — 4300 MPa
2. Tool Steel 1.2709 — 2355 MPa
3. Maraging Steels — 2080 MPa
4. Inconel 718 — 1532 MPa
5. Cobalt-Chrome — 1450 MPa
6. Titanium — 1426 MPa

7. Stainless Steel — 1100 MPa

Although metals lead in terms of ultimate tensile strength, fiber-reinforced polymers—such as those reinforced with carbon or Kevlar fibers—also demonstrate high strength-to-weight ratios. This makes them especially attractive for specific engineering applications where reduced weight is critical.

a. Ultimate Tensile Strength of Plastics

1. Nylon FR-A (carbon fiber reinforced) — 760 MPa
2. PETG (carbon fiber reinforced) — 740 MPa
3. Nylon (Kevlar reinforced) — 610 MPa
4. Carbon Fiber PEEK CF 9710 — 176 MPa

b. Flexural Strength. Flexural strength represents the maximum stress a material can withstand before breaking under bending forces. The higher this value, the more resistant the material is to flexural loads. For instance, in applications such as furniture design (e.g., benches or chairs), it is important to consider both the flexural strength and the expected service loads. Materials with high flexural strength provide an essential safety margin during operation [3].

c. Flexural Strength of Selected Materials

1. Carbon Fiber Reinforced PEEK — 175 MPa
2. Carbon Fiber Reinforced Nylon — 175 MPa
3. PEEK — 130 MPa
4. Glass Fiber Reinforced Nylon — 125 MPa
5. Polycarbonate — 92 MPa
6. PLA — 89 MPa
7. Nylon (Polyamide) — 70 MPa

Flexural strength should also be distinguished from the flexural modulus, which characterizes a material's stiffness under bending. For thin-walled components (e.g., tubes or shells), materials with a high flexural modulus are preferable to prevent deformation under external loads.

The elastic modulus (Young's modulus) defines a material's ability to return to its original shape after deformation. It is expressed as the ratio of stress to strain. For example, TPU has a low elastic modulus (approximately 70 MPa), making it soft and flexible, whereas most PEEK filaments exhibit a much higher modulus (up to 3720 MPa), which gives them significant rigidity [4, 5].

Another important parameter is elongation at break, which indicates how much a material can stretch before failure. For instance, TPU can reach elongation values of up to 400%

d. Materials with the Lowest Elastic Modulus

1. Silicone — 2.5 MPa
2. TPU — 5.3 MPa
3. Flexible photopolymer resins — 6.4 MPa
4. TPE — 8 MPa
5. Silicone-like resins — 8.7 MPa

e. Impact Strength (Toughness). Impact strength reflects a material's resistance to failure under sudden loads (such as impact or drops). This parameter is critical for evaluating the reliability of a product in extreme operating conditions. It is typically determined using standardized tests, such as the notched Izod impact test.

f. Notched Izod Impact Strength:

1. Polycarbonate (PC) — 800 J/m²
2. HIPS — 350 J/m²
3. ABS — 215 J/m²
4. Polypropylene (PP) — 160 J/m²
5. Carbon fiber reinforced PEEK — 130 J/m²

III. RESEARCH METHODS

Tensile strength measures the maximum load or force a material can withstand before it breaks or fractures. This property is typically expressed in megapascals (MPa) or pounds per square inch (psi).

Young's modulus, or the modulus of elasticity, quantifies how resistant a material is to deformation under load. A high Young's modulus indicates that the material is stiff and does not bend or deform easily when force is applied. It is also measured in MPa or psi.

It is important to note that strength and stiffness are not always directly correlated. Some materials may exhibit high tensile strength but a low Young's modulus, making them strong yet flexible. Conversely, other materials may be very stiff but have low tensile strength, making them brittle under stress.

Additional mechanical properties include compressive strength and flexural strength, which reflect a material's resistance to compression and bending, respectively. Impact toughness and hardness are also crucial indicators of performance, particularly under sudden or localized stresses.

To accurately compare different materials, one must consult the manufacturer's technical datasheets, as mechanical properties can vary significantly depending on the specific composition and processing of the material.

Tensile strength, in particular, reflects a material's ability to resist stretching or tension before breaking. This is typically measured by securing a sample in a device similar to a vise and applying tensile force in opposite directions. From a practical perspective, this indicates how quickly a part might fail under load or how brittle it may be. For example, the ultimate tensile strength of stainless steel is around 860 MPa, while that of glass is approximately 33 MPa, and consumer-grade PLA is about 53 MPa [6, 7, 8].

IV. IMPACT TOUGHNESS AND HARDNESS

Impact toughness, also referred to as impact strength or resistance to fracture under sudden force, is a critical characteristic for evaluating how well a part can withstand shocks or drops. This property is typically measured in joules per square meter (J/m^2) or foot-pounds per square inch ($ft{\cdot}lb/in^2$) and can be determined through various standardized tests, such as the Izod or Charpy impact test, depending on the material.

Hardness, on the other hand, reflects a material's resistance to scratching, abrasion, or indentation. It is commonly measured using the Rockwell or Shore hardness scales, both of which are frequently applied to polymers. Shore hardness is a general indicator of a material's surface stiffness; for instance, Shore 95A indicates a relatively firm elastomer, often used to describe flexible filaments like TPU [9, 10].

V. RESULTS

To ensure durability and strength in 3D-printed parts, it is essential not only to select the appropriate material but also to consider a range of additional factors that significantly influence mechanical performance. These factors include print orientation, infill parameters, layer and wall thickness, as well as post-processing techniques. Proper optimization of these settings can substantially enhance the part's resistance to operational loads.

Furthermore, when designing models, it is important to account for the specific features of the 3D printing technology being used and the expected functional stresses on the part. Adhering to design best practices facilitates the production of more reliable and robust components.

In many cases, it is advisable to perform thermal post-processing — specifically, annealing. This procedure reduces residual internal stresses, improves interlayer adhesion, and stabilizes the material's structure. Annealing is particularly relevant for high-temperature polymers such as PEEK but can also be effectively applied to materials like ABS, PLA, and nylon to enhance their mechanical properties.

VI. ANNEALING AND FINAL ANALYSIS

Annealing is a method of thermal treatment primarily used for metals to enhance their ductility and workability. During annealing, materials are heated to an optimal temperature—below their melting point but above their recrystallization temperature. When metals are cast or formed, they develop fine crystalline structures known as grains, which define the material's microstructure. Smaller grains typically result in a harder but more brittle material. Increasing grain size through annealing reduces hardness and improves ductility, making the material easier to process. The process involves heating the material to a temperature at which grain recrystallization and growth occur. The duration of exposure at this temperature affects the degree of structural change.

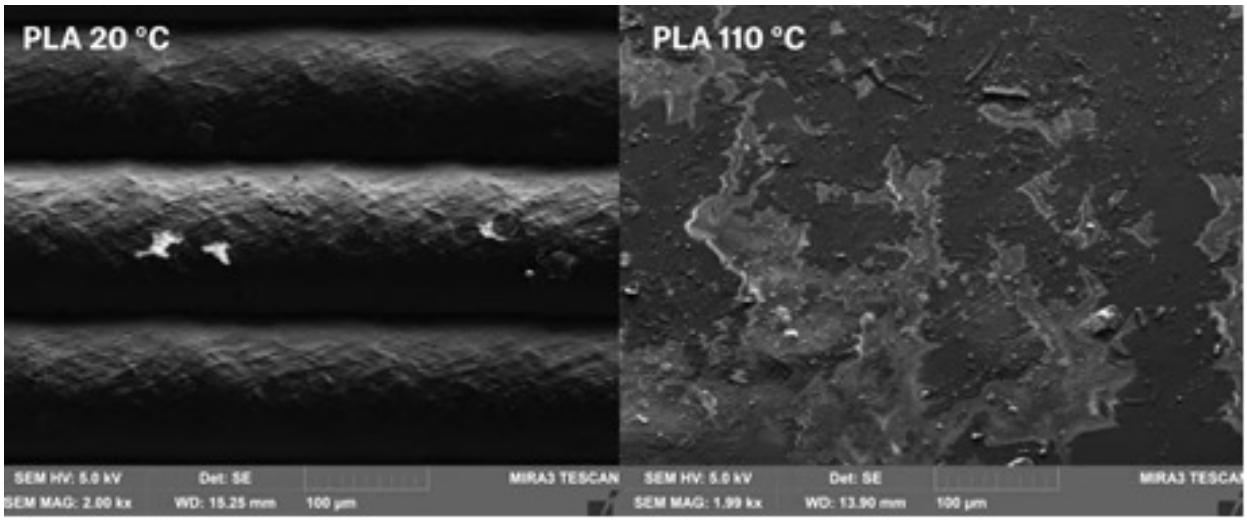


Figure 1. Enlarged image of standard and annealed PLA at 110°C.

Although annealing is primarily associated with metals, a similar process is used for plastics. In plastic injection molding, annealing helps relieve internal stresses within the parts. This involves heating the plastic parts below their melting point, allowing the material to relax and rearrange. However, in the case of 3D printing, the process differs somewhat. Plastics may exhibit various molecular structures, ranging from amorphous (completely disordered) to highly crystalline. Crystalline structures typically provide greater mechanical rigidity. Semi-crystalline materials such as PLA or PETG contain both amorphous and crystalline regions, with their ratio depending on the material's thermal history. Rapid heating and cooling during 3D printing increases the proportion of the amorphous structure. Annealing printed parts enables molecular chains to reorganize and form crystalline domains. As with metals, this leads to improved mechanical properties. Partial remelting may also occur, enhancing interlayer bonding and eliminating weak points in the printed object.

Through analysis of the mechanical properties of materials used in 3D printing, key indicators such as tensile strength, stiffness, and impact resistance have been identified as crucial for selecting appropriate materials for functional parts.

Metals remain the leaders in tensile strength, with the highest values observed in Vibenite 290 (up to 4300 MPa), tool steel (2355 MPa), and maraging steels (2080 MPa). Among polymers, the best performance is shown by nylon- and PETG-based composites reinforced with continuous carbon or Kevlar fibers. Nylon FR-A reaches up to 760 MPa in tensile strength, while PETG reaches 740 MPa. Flexural strength is critical for parts subject to bending loads, with PEEK and carbon fiber-reinforced nylon performing best at 175 MPa. PLA and polycarbonate fall behind, with values around 89–92 MPa. The Young's modulus reflects a material's ability to recover its shape after deformation. High stiffness was observed in PEEK ($\sim$3720 MPa), while flexible materials such as TPU and silicone showed low values (5–8 MPa), making them suitable for applications requiring elasticity. The highest impact strength was recorded for polycarbonate (800 J/m²), making it an excellent choice for parts subject to drops or shocks. Other materials with good impact resistance include HIPS (350 J/m²) and ABS (215 J/m²).

VII. CONCLUSION

The results indicate that material selection should be based on the expected mechanical loads. Reinforced polymers and metals are preferable for high tensile and flexural strength. For impact resistance, polycarbonate is most suitable. For applications requiring flexibility, TPU and similar elastomers are ideal. These findings provide a solid foundation for the rational design of durable 3D-printed structures.

REFERENCES

1. S. Lim, R. Buswell, T. Le, R. Wackrow, S. Austin, A. Gibb, T. Thorpe, Development of a viable concrete printing process, in: Proc. 28th Int. Symp. Autom. Robot. Constr. ISARC 2011, 2011, pp. 665–670.

2. R.A. Buswell, R.C. Soar, A.G.F. Gibb, A. Thorpe, Freeform construction: mega-scale rapid manufacturing for construction, Autom. Constr. 16 (2007) 224–231.

3. F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, Virtual Phys. Prototyp. 11 (2016) 209–225.

4. M. Skitmore, 3D printing in the construction industry : a review abstract construction 3Dp, Int. J. Constr. Manag 15 (2015) 1–13.

5. The National, Dubai unveils world's largest 3D printed two-store building. https ://www.thenationalnews.com/uae/government/dubai-unveils-world-s-largest-3d- printed-two-storey-building-1.927590 (accessed May 8, 2022).

6. P. Kmiecik, M. Kami´nski, Modelling of reinforced concrete structures and composite structures with concrete strength degradation taken into consideration, Arch. Civ. Mech. Eng. 11 (2011) 623–636.

7. C.-S.C. Beak-Il Bae, Hyun-Ki Choi, Flexural strength evaluation of reinforced concrete members with ultra high performance concrete, 2016 (2016) 10.

8. Y.J. Park, A.H.S. Ang, Y.K. Wen, Seismic damage analysis of reinforced concrete buildings, J. Struct. Eng. (United States) 111 (1985) 740–757.

9. Y. Zhou, X. Cui, Experimental study on static and fatigue properties of CFRP reinforced concrete beams, IOP Conf. Ser. Earth Environ. Sci. 376 (2019) 1–7.

10. L. Chung, M.W. Hur, T. Park, Performance Evaluation of CFRP reinforced concrete members utilizing fuzzy technique, Int. J. Concr. Struct. Mater. 12 (2018) 1–11.