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Comparative Analysis of Polymer Additive Manufacturing Processes Through Harmonized Mechanical Performance Evaluation

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Abstract
This study presents a harmonized comparison of polymer additive manufacturing processes under uniform ASTM and ISO protocols. Specimens were produced by fused deposition modelling with ABS and ASA, stereolithography with rigid and tough resins, and selective laser sintering with PA12. Tensile, flexural, impact, and hardness tests were conducted with five replicates per condition. SLA rigid resin delivered the highest stiffness and tensile strength yet showed negligible ductility and brittle failure. In flexure it was nearly six times stiffer than FDM ABS and SLS PA12 but failed catastrophically, whereas tough SLA traded modulus for meaningful elongation. FDM exhibited moderate strength with the greatest elongation and the highest impact energy absorption, consistent with ductile yielding and crack deflection at inter-bead voids. SLS PA12 achieved a balanced profile, with modulus and strength between FDM and SLA, improved isotropy in the XY plane, and higher toughness after post annealing. Hardness tracked stiffness, with SLA rigid around Shore D 85, PA12 near 80, and FDM in the low 70s. The unified dataset provides application-driven guidance for process and parameter selection and motivates future work on fatigue, creep, fracture toughness, environmental aging, and life cycle assessment. Results are directly translatable to stiffness-critical, impact-tolerant, and balanced performance use cases.

Keywords: *Additive manufacturing; Fused Deposition Modeling; Stereolithography; Selective Laser Sintering; Tensile strength; Flexural behavior; Impact toughness; Anisotropy.*

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I. INTRODUCTION

Additive manufacturing, commonly known as three-dimensional printing, has transformed engineering practice by enabling geometric complexity, on demand production, and reduced material waste [1]. Initially confined to rapid prototyping, additive manufacturing is now pervasive in aerospace, automotive, biomedical, and consumer sectors, where layer by layer fabrication offers a shift from subtractive and formative methods and unlocks design freedom with improved material efficiency [2]. Among polymer additive manufacturing technologies, three processes dominate industrial adoption and research focus: Fused Deposition Modeling, Stereolithography, and Selective Laser Sintering. Their distinct consolidation mechanisms, extrusion bonding for Fused Deposition Modeling, photopolymerization for Stereolithography, and powder bed fusion for Selective Laser Sintering, produce markedly different mechanical responses and reliability profiles [3][4][5].

Mechanical reliability remains the principal barrier to replacing conventionally manufactured parts. Performance metrics such as tensile strength, elastic modulus, elongation at break, flexural behavior, impact toughness, and hardness are highly process and parameter dependent. In Fused Deposition Modeling, raster orientation, layer height, and infill geometry govern interlayer bonding and anisotropy. Aligning raster with the tensile axis increases strength but does not eliminate weak interfaces; Z oriented specimens often fail by delamination and can exhibit tensile strength that is less than half of XY oriented samples [3][6]. Infill geometry alters stress distribution, with honeycomb and similar architectures outperforming rectilinear patterns in energy absorption [7]. Typical Shore D hardness for ABS and ASA is in the low seventies, consistent with ductility rather than high stiffness, while thermal annealing can increase stiffness and strength by reducing voids, although dimensional distortion may result [8][9].

In Stereolithography, resin chemistry and post curing define the stiffness ductility trade off. Rigid epoxy like resins deliver high modulus and tensile strength but exhibit elongation at break that is typically less than one percent, a sign of brittle behavior. Toughened photopolymers increase elongation beyond forty percent yet sacrifice modulus and strength [5][4][10]. Flexural properties of rigid Stereolithography parts are correspondingly high, with flexural modulus reported near nineteen gigapascals and flexural strength around one hundred megapascal, yet failure is often catastrophic without plastic deformation [4]. Environmental exposure matters as well. Moisture uptake can reduce modulus and compromise long term durability of cured resins [11].

In Selective Laser Sintering, the physics of powder fusion and thermal history govern strength, ductility, and isotropy. With PA12, tensile strengths of about 45-55MPa and elongation of eight to twelve percent are common, values that approach injection moulded nylon under favourable conditions. Anisotropy is modest, with Z direction properties slightly lower due to incomplete sintering across layers [12] [13]. Reported flexural modulus typically lies between one point six and one point eight gigapascals, while impact resistance is intermediate and improves with thermal annealing that relieves residual stress [11][12]. Process economics and sustainability also shape technology choice. Stereolithography resins are petrochemical and generate hazardous liquid waste, complicating recycling. Fused Deposition Modeling can utilize biodegradable PLA but sacrifices toughness relative to ABS or ASA. Selective Laser Sintering enables partial powder recyclability, yet repeated reuse oxidatively ages powder and reduces toughness [2][14][15].

Comparative studies emphasize these trade-offs but often lack harmonized protocols that allow direct engineering grade comparisons. [4] Reported Stereolithography superiority in stiffness relative to Fused Deposition Modeling under ASTM testing, while [5] found that Stereolithography consistently achieved higher tensile strength, about forty five megapascal versus about 27MPa for Fused Deposition Modeling at 100% infill, and higher modulus, about 2085MPa versus 1804MPa. [5] Also noted practicality concerns when deformation increases with infill in Stereolithography. These findings reinforce the prevailing view that Stereolithography dominates in stiffness and Fused Deposition Modeling in toughness, yet neither source included Selective Laser Sintering. That omission limits process selection for end use parts that require a balanced property set and near isotropic behavior. Harmonized, cross technology datasets are therefore necessary to enable defensible, application driven decisions for structural and safety critical contexts [4][5].

Sustainability considerations further motivate comparative, standardized evidence. Lifecycle assessments indicate that material choice and post processing strongly influence environmental burdens, including energy consumption and waste streams. Powder reuse in Selective Laser Sintering must be balanced against mechanical degradation. Resin waste and solvent handling remain concerns in Stereolithography. In Fused Deposition Modeling, bio-based feedstocks can reduce environmental impact but may not satisfy toughness or heat resistance requirements in service [2][14][15].

Minimal problem statement. Despite rapid advances, there is still no unified benchmark that compares Fused Deposition Modeling, Stereolithography, and Selective Laser Sintering under identical standards while also integrating Selective Laser Sintering with PA12. Prior studies frequently rely on disparate geometries and environmental conditions, which impedes direct comparison and informed process selection. Sustainability is inconsistently incorporated, further complicating decisions [4][5][14][15].

The present work standardizes tensile, flexural, impact, and hardness testing under ASTM and ISO for ABS and ASA in Fused Deposition Modeling, for rigid and toughened resins in Stereolithography, and for PA12 in Selective Laser Sintering. Fatigue, creep, fracture toughness, and long-term aging are beyond the present scope. Parameters reflect baseline, industrially relevant settings. Sustainability is discussed qualitatively to frame trade-offs and to connect mechanical performance with environmental constraints and material stewardship [1][2][3][4][5][6][7][8][9][10][11][12][13][14][15].

Taken together, the evidence base shows that no single process is universally superior. Stereolithography offers unmatched stiffness and surface finish but brittleness and sensitivity to environment. Fused Deposition Modeling delivers ductility and impact tolerance with anisotropy that must be managed through orientation and process tuning. Selective Laser Sintering provides a balanced and often near isotropic profile at the expense of careful powder management and thermal control [4][5][12][13]. This study addresses the need for a harmonized comparison and extends prior work by placing all three processes under consistent standards with clear scope and limitations.

II. METHODOLOGY

This study adopts a comparative experimental framework to systematically evaluate the mechanical properties of parts produced by FDM, SLA, and SLS under harmonized conditions. Methods integrate standardized specimen preparation, controlled printing, mechanical testing, microstructural analysis, and statistical evaluation. The approach builds on previous investigations [4][5] while extending scope to include all three major polymers AM processes. FDM used industrial-grade ABS and ASA filaments (1.75 mm; ABS from PlastikaTrček; ASA chosen for UV resistance), extruded at 230–240 °C with a 0.4 mm brass nozzle on a 90–100 °C bed. SLA employed rigid epoxy-like and toughened resins on an Anycubic HALOT-MAGE PRO 8K (0.05 mm layers); parts were IPA-washed and UV-cured (405 nm, ~30 min) [5]. SLS used PA12 (PA2200) powder with ~70 W laser, 170–180 °C bed, 0.10–0.12 mm layers; post-processing included depowdering and bead-blasting, plus annealing for a subset [11].

Table 1: Standardized Specimen Geometries and Tests [3][5]

S/N	Test type	Standard(s)	Specimen / method notes
1	Tensile testing	ASTM D638 Type I; ISO 527-2:2012	Dog-bone tensile specimens; gauge length and thickness per standard
2	Flexural testing	ASTM D790	Three-point bending; span-to-depth ratio 16:1
3	Impact testing	ASTM D256	Notched Izod geometry; specified V-notch dimensions
4	Hardness	ASTM D2240; ASTM E384	Shore D durometer (polymers); Vickers micro hardness for SLA/SLS cross-sections

All specimens above were conditioned at 23 °C and 50% RH for 48 hours before testing to standardize moisture absorption effects, particularly relevant for PA12.

Table 2: Printing Parameters of FDM, SLS and SLA

Table 2a: FDM Printing Parameters

S/N	Parameter	Value / Setting
1	Build orientations	XY plane (long axis aligned with raster); Z plane (vertical build)
2	Infill density	100% baseline; 30% hexagonal pattern for comparison
3	Layer thickness	0.2 mm
4	Raster orientation	0° and 45°
5	Cooling	Controlled fan speeds to minimize warping

Table 2b: SLA Printing Parameters

S/N	Parameter	Value / Setting
1	Build orientation	Flat XY plane for tensile bars; avoid angled supports to reduce stress concentrations
2	Post-curing	Manufacturer-specified cycle (UV + thermal)
3	Support structures	Removed manually; ensure no influence on gauge section

Table 2c: SLS Printing Parameters

S/N	Parameter	Value / Setting
1	Energy density	Calculated from laser power, scan speed, hatch spacing, and layer thickness
2	Powder refresh ratio	50% virgin + 50% recycled powder (industrial practice)
3	Post-build anneals	150 °C for 2 hours (subset) to evaluate stress-relief effects

Table 3: Mechanical Testing Overview [4][5]

S/N	Test type	Equipment / Setup	Key parameters	Outputs
1	Tensile testing	Instron 5969; Zwick Z100 universal testers	Crosshead speed: 5 mm/min; extensometer attached within gauge length	Young's modulus; yield stress; ultimate tensile strength (UTS); elongation at break
2	Flexural testing	Three-point bending fixture	Span-to-depth ratio: 16:1; loading rate per ASTM D790	Flexural modulus; flexural strength
3	Impact testing	Izod impact tester	Notched Izod method per ASTM D256; energy recorded	Impact energy (kJ/m²)
4	Hardness testing	Shore D durometer; Vickers microhardness setup	Shore D for polymers; Vickers: 200 g load, 15 s dwell; triplicate measurements averaged	Shore D hardness; Vickers hardness (HV)

Table 4: Microstructural Analysis Summary [4][9][12]

S/N	Process	Imaging methods	Observed features	Interpretation / failure mechanism
1	FDM	SEM; optical microscopy	Inter-bead voids; partial interlayer fusion gaps	Crack initiation and delamination along weak interlayer interfaces; anisotropic tensile/flexural response
2	SLA	SEM; optical microscopy	Brittle cleavage planes; resin crosslink features	Low energy absorption; catastrophic brittle fracture; high stiffness but poor impact resistance
3	SLS	SEM; optical microscopy	Partially sintered particle boundaries; porosity distribution	Mixed ductile–brittle behavior depending on energy density; near-isotropy when sintering is optimized

Table 5: Material specifications (ABS, ASA, SLA rigid/tough resin, PA12). [5]

S/N	Material	Process	Form	Typical Density (g/cm³)	Glass Transition Temp (Tg, °C)	Processing Temperature (°C)	Key Properties
1.	ABS	FDM	Filament (1.75	1.04–1.06	~105	Extrusion: 230–250	Good toughness,

	(Acrylonitrile Butadiene Styrene)		mm)			Bed: 90–100	ductile, prone to warping
2.	ASA (Acrylonitrile Styrene Acrylate)	FDM	Filament (1.75 mm)	1.07–1.08	~100	Extrusion: 230–250 Bed: 90–100	UV-stable, weather resistant, similar strength to ABS
3.	SLA Rigid Resin (epoxy-based)	SLA	Photopolymer liquid	1.12–1.20	~110–120	Cured at 405 nm (UV) + post-bake	High stiffness, brittle failure, smooth surface finish
4.	SLA Tough Resin (toughened formulation)	SLA	Photopolymer liquid	1.10–1.15	~80–90	Cured at 405 nm (UV) + post-bake	Higher ductility, lower stiffness, impact-resistant
5.	PA12 (Polyamide 12 / Nylon 12)	SLS	Powder (20–60 μm size)	1.01–1.02	~50–55 (Tg) Melt: ~178–182	Laser sintering bed: 170–180	Balanced strength-toughness, chemical resistance, near-isotropic

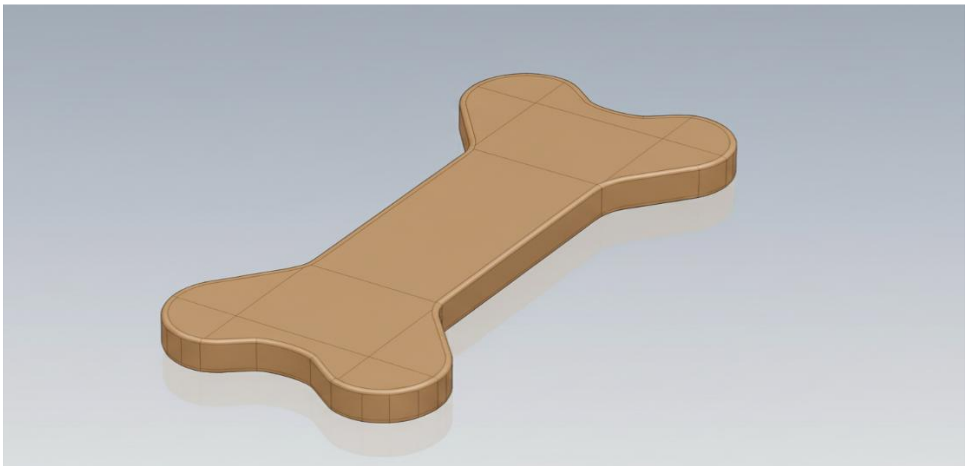
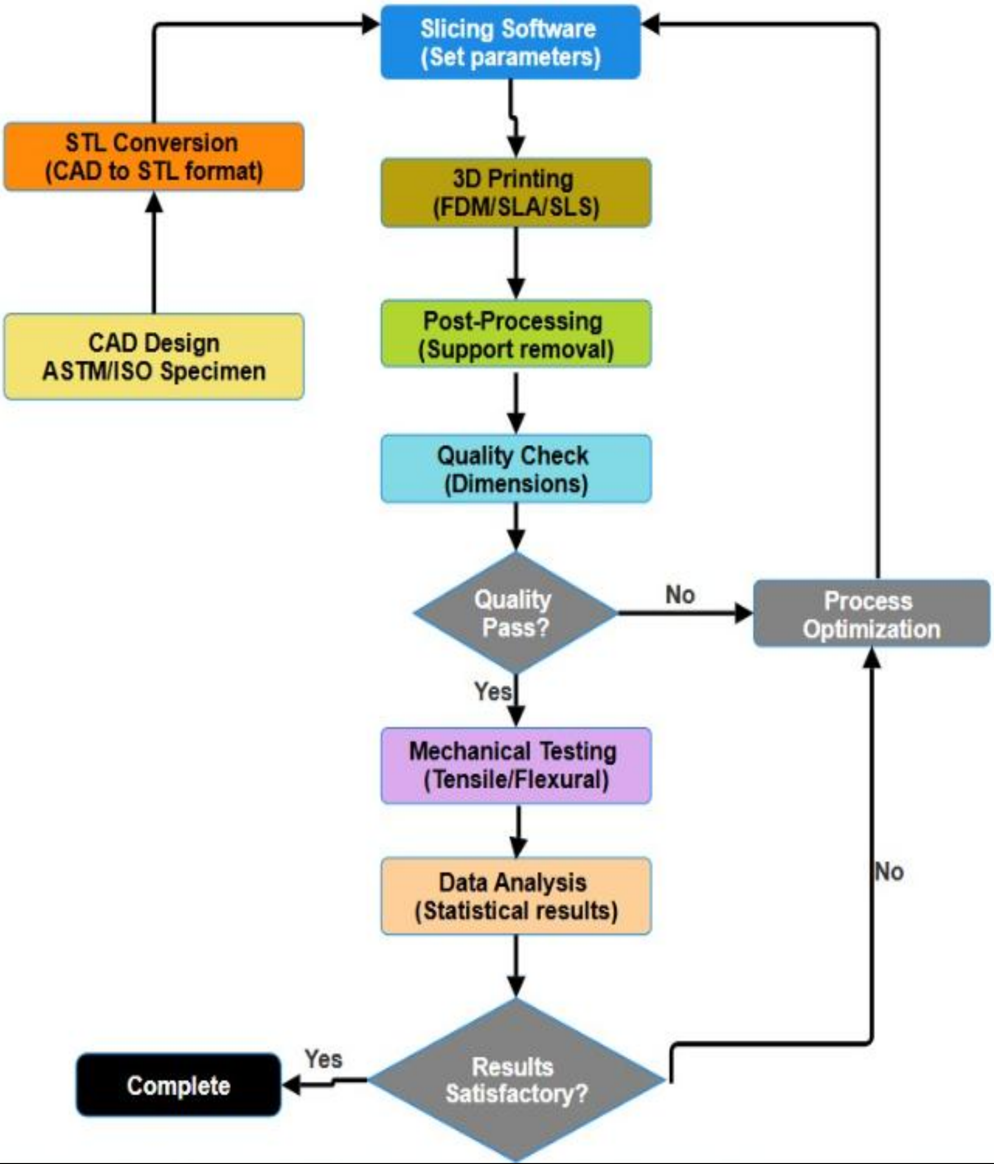


Figure 1: CAD designs of Dog-Bone Tensile Specimen.

Figure 2: FDM, SLA, and SLS dog-bone tensile specimen post-printing.

Table 6: Printing parameters (orientation, layer thickness, infill, curing, and energy density).

Parameter	FDM	SLA	SLS
Layer Thickness (mm)	0.1 - 0.3	0.025 - 0.15	0.06 - 0.15
Orientation	0°, 45°, 90°	0° - 90°	0° - 90°
Infill Density (%)	15 - 100	N/A (Solid)	N/A (Solid)
Print Speed (mm/s)	30 - 100	N/A	100 - 5000
Nozzle Temperature (°C)	190 - 230	N/A	N/A
Bed Temperature (°C)	50 - 110	N/A	80 - 200



Laser Power (W)	N/A	N/A	10 - 40
Energy Density (J/mm³)	N/A	N/A	0.1 - 0.5
Curing Time (s)	N/A	1 - 10	N/A
Support Material	Required	Required	Not required
Post-Processing	Support removal, sanding	Washing, UV curing	Powder removal, blasting

Figure 3: Schematic workflow of experimental methodology.

III. RESULT AND DISCUSSION

Mechanical tests revealed clear distinctions among FDM, SLA, and SLS in terms of tensile, flexural, impact, and hardness properties. Results reported below represent mean values from at least five replicates per condition, with standard deviations included. Comparative interpretation highlights how consolidation mechanisms shape performance profiles.

Table 7: Tensile properties of FDM, SLA, and SLS specimens (mean ± SD). [3][4][5]

S/N	Process / Material	Young's Modulus (GPa)	UTS (MPa)	Elongation at Break (%)	Notes
1	FDM (ABS)	0.72 ± 0.12	50 ± 9	26 ± 5	XY build, 0° raster
2	FDM (ASA)	0.73 ± 0.11	45 ± 6	23 ± 5	UV-stabilized, similar to ABS
3	SLA (Rigid resin)	3.58 ± 0.09	87 ± 18	0.6 ± 0.1	Post-cured, brittle fracture
4	SLA (Tough resin)	0.61 ± 0.16	37 ± 6	45 ± 1	Elastomer-modified, ductile
5	SLS (PA12)	1.85 ± 0.12	50 ± 4	11 ± 3 (XY) / 6 ± 2 (Z)	Moderate anisotropy

SLA rigid resin achieved the highest modulus and ultimate tensile strength, confirming superior stiffness but negligible ductility. FDM ABS/ASA showed moderate strength with high elongation and clear ductile yielding. SLS PA12 provided a balanced profile, with modulus above FDM but below SLA, and elongation indicative of moderate toughness. Comparative tensile data (~45 MPa for SLA versus ~27 MPa for FDM at 100% infill) further underscore SLA's stiffness advantage.

Table 8: Flexural properties across processes. [12]

S/N	Process / Material	Flexural Modulus (GPa)	Flexural Strength (MPa)	Notes
1	FDM (ABS)	3.04 ± 0.10	50 ± 1.5	Ductile bending
2	FDM (ASA)	2.98 ± 0.36	45 ± 1.3	Slightly weaker
3	SLA (Rigid resin)	18.7 ± 0.13	99 ± 8.8	Very stiff, brittle fracture
4	SLA (Tough resin)	4.73 ± 0.19	64 ± 3.1	Improved ductility
5	SLS (PA12)	1.6–1.8	~66	Process dependent

SLA rigid resin exhibited nearly six fold higher flexural stiffness than FDM ABS and SLS PA12 but failed catastrophically in bending. Switching to a tough SLA resin reduced stiffness while adding meaningful ductility. FDM specimens showed stable, ductile bending; microscopy indicated crack initiation at inter-bead voids. SLS PA12 achieved flexural strength comparable to FDM and displayed better isotropy, particularly in XY builds.

Table 9: Impact Resistance Performance [9][11]

S/N	Process / Material	Impact Energy (kJ/m²)	Qualitative Behavior	Post-processing
1	FDM (ABS/ASA)	Highest among the three	Ductile; void-mediated crack arrest	Toughness enhanced by inter-bead voids
2	SLA (Rigid resin)	~5	Brittle; fractures at very low energy	Tough resin variant improves slightly
3	SLS (PA12)	~15	Intermediate toughness	Improves further with annealing

Impact results confirmed the toughness vs stiffness trade-off.

Table 10: Hardness [10][13]

S/N	Process / Material	Shore D (approx.)	Vickers Hardness (HV)	Notes / Source
1	SLA (Rigid resin)	~85	>20	Highest hardness; correlates with high stiffness and brittleness
2	FDM (ABS/ASA)	~72–74	—	Lower hardness; consistent with ductile behavior.
3	SLS (PA12)	~80	—	Intermediate hardness; balanced stiffness–toughness

Trend: Hardness aligns with stiffness: **SLA > SLS > FDM**.

Table 11: Microstructural Analysis Summary

S/N	Process / Material	Observed (SEM/Optical) Features	Dominant Failure Mechanism	Implications for Properties
1	**FDM (ABS/ASA)**	Inter-bead voids; incomplete interlayer fusion	Layer delamination along weak interfaces	Pronounced anisotropy; reduced stiffness; higher impact tolerance due to crack deflection
2	**SLA (Rigid resin / Tough resin)**	Rigid: brittle cleavage, river-like patterns; Tough: rougher, ductile tearing	Rigid: brittle cleavage; Tough: mixed ductile tearing	Rigid: very high stiffness, low toughness; Tough: improved ductility with reduced modulus
3	**SLS (PA12)**	Partially sintered particle boundaries; porosity distribution	Optimized: ductile tearing; Under-sintered: brittle fracture	Near-isotropic strength when optimized; toughness sensitive to sintering energy and porosity

Table 8 shows flexural properties. SLA rigid resin achieves the highest flexural modulus (≈18–19 GPa) and strength (≈100 MPa) but fails without plastic deformation. Switching to a tough SLA resin reduces stiffness while adding useful bend ductility. FDM ABS/ASA sits near 3 GPa with stable, ductile bending. SLS PA12 is intermediate, with flexural strength in the mid-60 MPa range and better directional uniformity in XY builds.

Table 9 presents impact resistance performance. FDM absorbs the most impact energy owing to ductile yielding and crack deflection at inter-bead voids. SLA rigid fractures at very low energy (≈5 kJ/m²), while the tough resin improves only modestly. SLS PA12 delivers intermediate toughness (≈15 kJ/m²) and benefits further from post-build annealing.

Table 10 summarizes hardness. Trends follow stiffness: SLA rigid records the highest values (Shore D ≈85; Vickers >20), consistent with a highly cross-linked, brittle network. SLS PA12 clusters around Shore D ≈80, reflecting a balanced profile. FDM ABS/ASA resides in the low-70s, aligning with its ductile character.

Table 11 details microstructural analysis. SEM and optical microscopy show FDM voids and incomplete interlayer fusion that reduce stiffness yet help arrest cracks. SLA rigid reveals brittle cleavage and river patterns, whereas the tough resin displays rougher, more ductile tearing. SLS exhibits partially sintered particle boundaries; when energy density is optimized, fracture becomes more ductile and isotropy improves.

IV. CONCLUSION

This study delivers a harmonized comparison of FDM, SLA, and SLS polymers under uniform ASTM and ISO protocols, clarifying how process physics shape mechanical performance. In tension, SLA rigid resin achieved the highest modulus and ultimate tensile strength, confirming superior stiffness with negligible ductility. Comparative data around 45 MPa for SLA versus 27 MPa for FDM at 100 percent infill reinforce this advantage. FDM ABS and ASA provided moderate strength with high elongation and clear ductile yielding, while SLS PA12 offered a balanced profile with modulus above FDM but below SLA and elongation indicative of moderate toughness. In flexure, SLA rigid resin was nearly sixfold stiffer than FDM ABS and SLS PA12 but failed catastrophically. Tough SLA reduced stiffness while adding meaningful ductility. FDM showed stable, ductile bending with crack initiation at inter bead voids, and SLS PA12 matched FDM in flexural strength while exhibiting better isotropy in XY builds.

Microstructural analysis explained these outcomes. Interlayer voids and partial fusion in FDM promote anisotropy yet aid crack deflection. The highly crosslinked network in SLA rigid drives brittle cleavage. SLS reveals partially sintered boundaries that, when energy density is optimized and with post annealing, support ductile tearing and near isotropic behavior. Across replicates, inter process differences were consistent, with SLA showing the lowest variability and FDM the highest. Practically, no single additive manufacturing route is universally superior. SLA rigid suits stiffness critical, precision applications. FDM is advantageous where impact tolerance, ductility, and cost matter. SLS is preferred for end use parts requiring a balanced strength, toughness, and isotropy envelope. Future work should expand to fatigue, creep, fracture toughness, environmental aging, and life cycle assessment to support reliable and sustainable deployment of additive manufacturing in safety critical, high duty applications.

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