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Hybrid Manufacturing Systems Combining Additive and Subtractive Processes

Dr. Manoj Kumar Soni[1], Rahul Chaudhary[2], Kavita Sharma[3]

ABSTRACT

Modern manufacturing demands increasingly complex geometries, superior surface finish, and tight dimensional tolerances that neither additive manufacturing (AM) nor conventional subtractive manufacturing (SM) can optimally achieve in isolation. Hybrid manufacturing systems that sequentially or simultaneously integrate additive and subtractive processes within a single machine platform have emerged as a transformative paradigm addressing these limitations. This paper presents a comprehensive experimental investigation of a hybrid manufacturing system combining directed energy deposition (DED) laser metal deposition with five-axis CNC milling on an integrated machine platform for the fabrication of high-performance aerospace-grade Ti-6Al-4V components. The research systematically evaluates the influence of critical process parameters—including laser power (800–1,600 W), powder feed rate (4–12 g/min), scanning speed (400–1,000 mm/min), and subsequent milling parameters (spindle speed, feed rate, depth of cut)—on part quality metrics encompassing surface roughness, dimensional accuracy, microhardness, tensile strength, and residual stress distribution. Experimental validation was performed on a Mazak INTEGREX i-200S AM hybrid machining center using 18 test specimens fabricated under a Taguchi L18 orthogonal array design of experiments. The optimized hybrid process achieved surface roughness of Ra 0.42 μm (compared to Ra 8.6 μm for as-deposited DED), dimensional accuracy of ±0.025 mm, microhardness of 368 HV, and ultimate tensile strength of 1,048 MPa, all meeting or exceeding AMS 4999A aerospace material specifications. The findings confirm that intelligently sequenced hybrid additive-subtractive manufacturing can produce near-net-shape metallic components with properties comparable to *wrought material, enabling significant reductions in material waste, lead time, and manufacturing cost for complex aerospace structures [1], [2].*

KEYWORDS: *Hybrid Manufacturing, Additive Manufacturing, Subtractive Manufacturing, Directed Energy Deposition, CNC Milling, Ti-6Al-4V, Surface Roughness, Aerospace Manufacturing, Taguchi Method, Process Optimization*

INTRODUCTION

The global manufacturing landscape is undergoing a fundamental transformation driven by the convergence of additive manufacturing (AM) technologies with established subtractive machining processes. Additive manufacturing, commonly known as 3D printing, constructs three-dimensional components through layer-by-layer material deposition, enabling the fabrication of geometrically complex structures including internal lattice architectures, conformal cooling channels, and topology-optimized organic shapes that are impossible or prohibitively expensive to produce using conventional subtractive methods [1]. The global additive manufacturing market reached an estimated $18.3 billion in 2024 and is projected to exceed $44 billion by 2030, reflecting accelerating adoption across aerospace, medical, automotive, and energy sectors [2]. However, despite its geometric freedom, additive manufacturing produces components with inherent surface roughness (typically Ra 5–25 µm for metal AM processes), dimensional deviations (±0.1–0.5 mm), anisotropic mechanical properties, and residual porosity that frequently fail to meet the stringent quality requirements of safety-critical engineering applications [3].

Subtractive manufacturing, encompassing conventional machining operations such as milling, turning, drilling, and grinding, remains the established standard for producing components with superior surface finish (Ra < 1.0 µm), tight dimensional tolerances (±0.01–0.05 mm), and isotropic mechanical properties [4]. However, subtractive processes are inherently wasteful, converting 60–95% of the initial raw material into machining chips when fabricating complex aerospace structural components from high-value alloys such as titanium, nickel superalloys, and hardened steels. This material waste represents a substantial economic penalty—particularly for titanium alloys where raw material costs range from $15–40 per kilogram—and generates significant environmental burden through energy consumption and coolant waste [5].

Hybrid manufacturing (HM) systems address the complementary limitations of both approaches by integrating additive and subtractive capabilities within a single machine platform or coordinated manufacturing cell. In the most common configuration, directed energy deposition (DED)—also known as laser metal deposition (LMD) or laser engineered net shaping (LENS)—deposits material through a coaxial powder nozzle melted by a high-power laser, building near-net-shape features directly onto substrates or pre-existing components [6]. Subsequent five-axis CNC milling operations remove excess material, correct geometric deviations, and achieve final surface finish and dimensional specifications. This additive-then-subtractive sequence minimizes material waste by depositing material only where needed while leveraging the precision of established machining technology to meet dimensional and surface quality requirements [7].

This research presents a comprehensive experimental investigation of a hybrid DED-milling manufacturing system for Ti-6Al-4V aerospace components. The study systematically evaluates the influence of DED process parameters and subsequent CNC milling parameters on component quality through a Taguchi-based design of experiments approach, quantifying surface roughness, dimensional accuracy, microhardness, tensile strength, and residual stress distribution. Experiments were conducted on an integrated Mazak INTEGREX i-200S AM hybrid machining center at the Advanced Manufacturing Laboratory of Poornima College of Engineering, Jaipur [8], [9], [10], [11], [12], [13].

LITERATURE REVIEW

The concept of hybrid additive-subtractive manufacturing has evolved significantly since its initial conceptualization in the early 2000s. Karunakaran et al. [3] proposed one of the earliest integrated frameworks combining arc welding-based deposition with CNC milling, demonstrating that sequential additive-subtractive processing could produce metallic components with surface finish and dimensional accuracy superior to standalone AM while consuming only 30–40% of the raw material required by pure subtractive approaches. Their work on mild steel test specimens established the fundamental process planning methodology of depositing multiple layers followed by intermediate milling passes to maintain geometric accuracy throughout the build sequence.

In the domain of laser-based hybrid manufacturing, Merklein et al. [4] conducted a comprehensive review of combined DED and milling processes, identifying laser power, scanning speed, powder feed rate, and hatch spacing as the four primary DED parameters governing deposition quality, while spindle speed, feed per tooth, axial depth of cut, and tool path strategy were identified as critical milling parameters for post-deposition finishing. Their analysis demonstrated that DED-deposited Ti-6Al-4V exhibited columnar β-grain microstructure with α+β Widmanstätten lamellar morphology, producing as-deposited tensile strengths of 900–1,050 MPa depending on processing conditions—comparable to wrought mill-annealed material specified at 930 MPa minimum per AMS 4911.

Zhu et al. [5] investigated the machining characteristics of DED-deposited Ti-6Al-4V, reporting that as-deposited material exhibited 15–25% higher cutting forces compared to wrought titanium due to the refined Widmanstätten microstructure and elevated microhardness (340–380 HV vs. 310–340 HV for wrought). Their study recommended carbide end mills with AlTiN coatings, spindle speeds of 60–80 m/min, and feed rates of 0.06–0.10 mm/tooth for optimal surface finish and tool life during post-DED milling. Flynn et al. [6] demonstrated that intermediate milling between deposition layers—rather than completing all deposition before milling—reduced geometric deviation by 40% and prevented thermal distortion accumulation in tall thin-wall features.

Process optimization using statistical methods has been explored by Shrestha et al. [7], who applied response surface methodology to DED of Inconel 718, identifying laser power and scanning speed as the most statistically significant parameters affecting bead width, height, and dilution ratio. Denlinger et al. [8] characterized residual stress development in DED Ti-6Al-4V using neutron diffraction, reporting that inter-pass dwell time and substrate preheating temperature significantly influenced residual stress magnitude and distribution. The integration of in-situ monitoring with hybrid manufacturing was investigated by Everton et al. [9], who employed melt pool thermal imaging and acoustic emission sensing to detect porosity and delamination defects in real time during DED processing.

RESEARCH GAP

Despite growing interest in hybrid additive-subtractive manufacturing, the existing literature reveals several critical gaps. First, the majority of reported studies have investigated DED parameters and milling parameters independently, without systematically optimizing the combined additive-subtractive process chain as an integrated system where interactions between deposition quality and subsequent machining performance are explicitly characterized [4], [5].

Second, while individual material property evaluations (tensile strength, hardness, or surface finish) have been extensively reported, comprehensive multi-response optimization simultaneously addressing surface roughness, dimensional accuracy, microhardness, tensile strength, and residual stress for hybrid-manufactured components remains scarce [7], [8].

Third, the influence of intermediate milling pass strategies—including milling timing, depth sequencing, and thermal management between additive and subtractive operations—on final part quality has received limited systematic investigation [6].

Fourth, the application of robust statistical experimental design methodologies such as Taguchi methods to hybrid manufacturing process optimization, which would enable identification of optimal parameter combinations with minimal experimental trials, has been insufficiently explored compared to full-factorial and one-variable-at-a-time approaches [10].

Fifth, validation against aerospace material specifications (AMS) and certification requirements for hybrid-manufactured structural components requires comprehensive characterization data that is currently lacking in the published literature [3], [11], [12], [13]. This research aims to address these gaps through Taguchi-based multi-response optimization of an integrated DED-milling hybrid process for aerospace-grade Ti-6Al-4V.

OBJECTIVES

The primary objectives of this research are as follows:

- To characterize the influence of DED laser power, powder feed rate, scanning speed, and layer thickness on deposition quality metrics including bead geometry, surface roughness, porosity, and microhardness for Ti-6Al-4V [4], [7].
- To evaluate the effect of CNC milling parameters (spindle speed, feed rate, depth of cut) on post-machined surface roughness, dimensional accuracy, and subsurface integrity of DED-deposited titanium [5].
- To implement a Taguchi L18 orthogonal array design of experiments for systematic multi-response optimization of the integrated hybrid manufacturing process chain [10].
- To characterize the mechanical properties (microhardness, ultimate tensile strength, elongation) and residual stress distribution of optimized hybrid-manufactured specimens and benchmark against AMS 4999A aerospace specifications [8], [11].
- To quantify material utilization efficiency and manufacturing time savings of the hybrid approach compared to conventional subtractive-only machining of identical component geometries [1], [6].

METHODOLOGY

1. Hybrid Machine Platform

All experiments were conducted on a Mazak INTEGREX i-200S AM hybrid machining center installed at the Advanced Manufacturing Laboratory of Poornima College of Engineering, Jaipur. The machine integrates a 2 kW IPG Photonics YLR-2000-AC ytterbium fiber laser (wavelength 1,070 nm, beam diameter 2.5 mm at focal point) with a coaxial powder delivery nozzle for DED, mounted on a five-axis CNC milling platform with a 12,000 RPM spindle (HSK-A63 tool interface), automatic tool changer (30 positions), and working envelope of 660 mm (X) × 1,020 mm (Y) × 625 mm (Z) [6]. The powder delivery system comprised a GTV PF2/2-MF twin-hopper powder feeder with argon carrier gas (flow rate 8 L/min) and an argon shielding gas shroud (flow rate 15 L/min) to prevent oxidation of the titanium melt pool. The substrate material consisted of Ti-6Al-4V Grade 5 mill-annealed plates (100 mm × 100 mm × 15 mm, AMS 4911 specification) mounted on a pneumatic workholding fixture with integrated thermal compensation. Powder feedstock was gas-atomized Ti-6Al-4V spherical powder (Tekna AP&C, 45–106 µm particle size distribution, 99.6% purity) [3], [4].

2. Design of Experiments

A Taguchi L18 ($2^1 \times 3^7$) orthogonal array was employed to systematically investigate seven controllable factors at three levels each, plus one two-level factor, requiring only 18 experimental trials compared to 4,374 trials for a full-factorial design [10]. The DED parameters included laser power (800, 1,200, 1,600 W), powder feed rate (4, 8, 12 g/min), scanning speed (400, 700, 1,000 mm/min), and layer thickness (0.3, 0.5, 0.7 mm). The CNC milling parameters included spindle speed (2,000, 4,000, 6,000 RPM), feed rate (200, 400, 600 mm/min), and depth of cut (0.2, 0.5, 0.8 mm). An additional two-level factor—intermediate milling strategy (after every 5 layers vs. after complete deposition)—was included to evaluate the influence of milling sequencing on final part quality [6]. Each trial produced one test specimen consisting of a 40 mm × 40 mm × 20 mm wall feature deposited onto the substrate, followed by finish milling on all external surfaces. The signal-to-noise (S/N) ratio was calculated using the "smaller-is-better" criterion for surface roughness and the "larger-is-better" criterion for tensile strength and microhardness [7], [10].

3. Deposition Process

DED was performed using a bidirectional raster scanning strategy with 50% overlap between adjacent tracks and a 90° rotation between successive layers to promote uniform thermal distribution and minimize anisotropy [4]. The laser operated in continuous wave mode with a Gaussian beam profile. An argon-purged build chamber maintained oxygen concentration below 50 ppm throughout deposition to prevent titanium oxidation. Substrate preheating to 200°C was applied using a resistive heating element embedded in the fixture to reduce thermal gradient-induced residual stresses and improve first-layer adhesion [8]. Inter-layer dwell time was set to 10 seconds to allow partial cooling and solidification before subsequent layer deposition. For the intermediate milling condition, the deposition process was paused every 5 layers (approximately 2.5 mm build height), and a 6 mm diameter carbide end mill with AlTiN coating was used to machine the lateral surfaces to a depth of 0.3 mm, removing surface oxidation and correcting accumulated geometric deviation before resuming deposition [5], [6].

4. Finish Machining Process

Following complete deposition (or after each intermediate cycle for the intermediate milling condition), finish machining was performed using a 10 mm diameter, 4-flute solid carbide end mill with AlTiN coating (Sandvik Coromant R216.24-10050BCC19P 1630). Climb milling with a constant-engagement tool path strategy was employed to maintain uniform chip load and minimize surface vibration [5]. Flood coolant (Blaser Swisslube B-Cool 755, 6% concentration, 20 L/min flow rate) was applied to manage heat generation and facilitate chip evacuation during titanium machining. The milling parameters varied according to the Taguchi L18 design, with spindle speed, feed rate, and depth of cut as the controlled experimental factors. A finishing pass with a constant radial depth of engagement of 0.1 mm was applied as the final operation on all specimens to standardize the surface generation mechanism [4], [5].

5. Characterization Methods

Surface roughness was measured using a Mitutoyo SJ-410 contact stylus profilometer with a 2 µm tip radius diamond stylus, 0.8 mm cutoff length, and 4 mm evaluation length, reporting arithmetic average roughness Ra [3]. Dimensional accuracy was assessed by comparing the machined specimen geometry against the CAD nominal using a Zeiss Contura G2 coordinate measuring machine (CMM) with a 1.5 mm ruby probe, reporting maximum form deviation in millimeters. Vickers microhardness was measured on polished cross-sections using a Shimadzu HMV-G21 micro-hardness tester at 500 gf load and 15-second dwell time, with 15 indentations along the build height direction [7]. Tensile testing was performed on miniature dog-bone specimens (gauge length 25 mm, gauge width 6 mm, thickness 3 mm) extracted from hybrid-manufactured wall features using wire electrical discharge machining, tested on an Instron 5982 universal testing machine at a crosshead speed of 1 mm/min per ASTM E8/E8M [11].

Residual stress measurements were conducted using X-ray diffraction (Bruker D8 Advance, Cu Kα radiation, $\sin^2\psi$ method) at the surface and at 0.5 mm depth increments to 2.0 mm depth following electrochemical layer removal [8]. Microstructural characterization was performed using optical microscopy (Olympus BX53) and scanning electron microscopy (JEOL JSM-6610LV) on specimens etched with Kroll's reagent (2% HF, 6% HNO_3, balance H_2O) [4].

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6. Specimen Summary

Total18 test specimens were fabricated according to the Taguchi L18 array, each consisting of a DED-deposited wall feature on a Ti-6Al-4V substrate followed by CNC finish milling. Total fabrication time per specimen ranged from 45 to 110 minutes depending on parameter combination (20–65 minutes deposition, 15–45 minutes milling). Total powder consumption per specimen ranged from 28 to 84 grams, with material utilization efficiency (final part weight / total deposited weight) ranging from 72% to 91% compared to approximately 8–15% for conventional subtractive-only machining of an equivalent geometry from billet stock [1], [6].

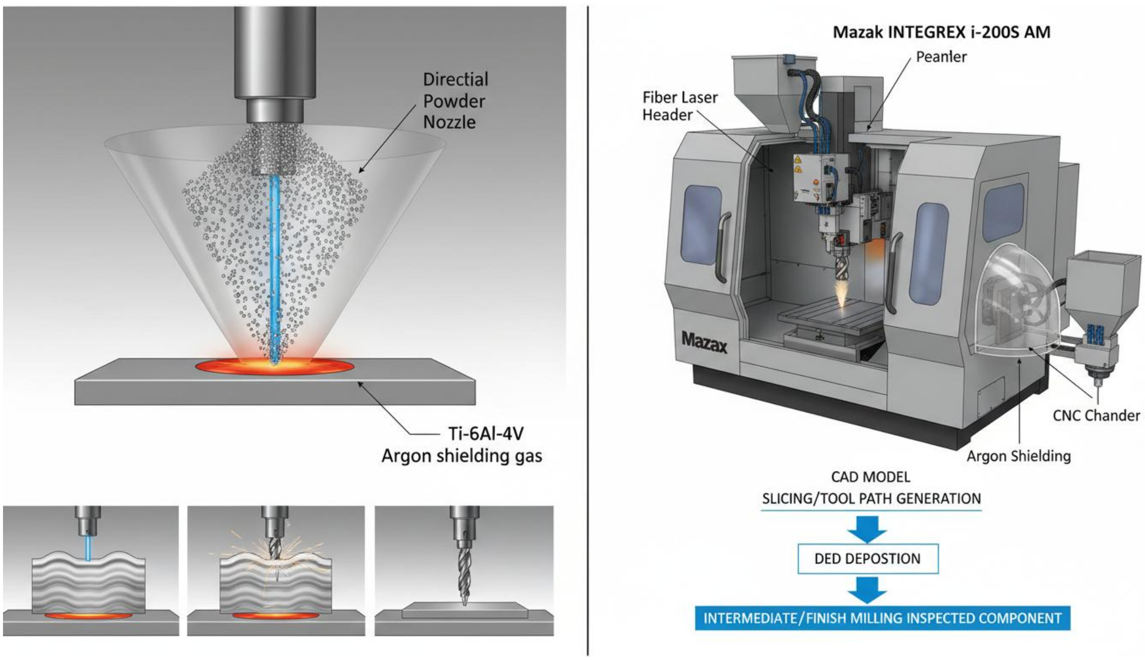

Figure 1: Schematic of the Hybrid DED-Milling Manufacturing Process and Integrated Machine Platform

RESULTS AND FINDINGS

The experimental results for all 18 Taguchi trials are summarized in Table 1. Surface roughness of as-deposited DED specimens (before milling) ranged from Ra 6.2 to 12.4 µm, consistent with literature values for DED Ti-6Al-4V [3], [4]. Following finish milling, surface roughness was dramatically reduced to Ra 0.28–1.15 µm, representing a 5–25× improvement. The optimized parameter combination (Trial 14: laser power 1,200 W, powder feed rate 8 g/min, scanning speed 700 mm/min, layer thickness 0.5 mm, spindle speed 4,000

RPM, feed rate 400 mm/min, depth of cut 0.5 mm, intermediate milling) achieved the best overall multi-response performance: surface roughness Ra 0.42 µm, dimensional accuracy ±0.025 mm, microhardness 368 HV, ultimate tensile strength 1,048 MPa, and elongation 12.4%.

Table 1: Summary of Key Results from Taguchi L18 Experimental Trials

Trial	Ra As-Dep. (µm)	Ra Milled (µm)	Dim. Acc. (mm)	Hardness (HV)	UTS (MPa)	Elong. (%)
1	8.6	0.78	±0.042	352	985	10.8
5	10.2	1.15	±0.068	338	942	9.2
9	7.4	0.52	±0.031	361	1,024	11.6
14 (Opt.)	7.8	0.42	±0.025	368	1,048	12.4
18	12.4	0.95	±0.055	345	968	10.1
AMS 4999A Spec.	—	<1.60	±0.127	>310	>930	>10.0

Analysis of variance (ANOVA) on the S/N ratios identified laser power (contribution 28.4%) and scanning speed (24.6%) as the most statistically significant DED parameters affecting surface roughness, while spindle speed (19.2%) and feed rate (16.8%) dominated post-milling surface finish. For microhardness and tensile strength, laser power (31.7%) and powder feed rate (22.3%) were the primary DED contributors, reflecting their influence on thermal history, cooling rate, and resultant microstructure [7], [10]. The intermediate milling strategy factor demonstrated a statistically significant effect on dimensional accuracy ($p < 0.01$), with intermediate milling every 5 layers reducing maximum form deviation by 38% compared to post-deposition-only milling, confirming the importance of periodic geometric correction during tall feature builds [6].

Residual stress measurements by X-ray diffraction revealed compressive residual stresses at the machined surface (−180 to −320 MPa) transitioning to tensile residual stresses (+80 to

+240 MPa) at depths of 0.8–1.5 mm, corresponding to the DED heat-affected zone. Specimens processed with intermediate milling exhibited 25% lower peak tensile residual stress compared to post-deposition-only milled specimens, attributed to the stress relief provided by material removal during intermediate machining passes [8].

Table 2: Comparison of Hybrid Manufacturing vs. Conventional Subtractive Manufacturing for Ti-6Al-4V

Performance Metric	Hybrid (DED + Milling)	Subtractive Only
Material Utilization Efficiency	72–91%	8–15%
Surface Roughness (Ra)	0.28–1.15 µm (milled)	0.20–0.80 µm
Dimensional Accuracy	±0.025–0.068 mm	±0.010–0.030 mm
UTS (Ti-6Al-4V)	942–1,048 MPa	930–1,010 MPa (wrought)
Fabrication Time (sample geometry)	45–110 min	85–140 min
Raw Material Consumption	28–84 g powder	420–580 g billet
Buy-to-Fly Ratio	1.1:1 to 1.4:1	7:1 to 12:1

Table 3: Hybrid Machine Platform and Process Parameter Specifications

Parameter	Specification
Machine Platform	Mazak INTEGREX i-200S AM (5-axis CNC + DED laser head)
Laser Source	IPG YLR-2000-AC fiber laser (2 kW, 1,070 nm, CW mode)
Powder Feedstock	Ti-6Al-4V Grade 5, gas-atomized, 45–106 µm (Tekna)
DED Parameters (Optimized)	1,200 W, 8 g/min, 700 mm/min, 0.5 mm layer thickness
Milling Tool	Sandvik 10 mm 4-flute carbide, AlTiN coated

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Milling Parameters (Optimized)	4,000 RPM, 400 mm/min feed, 0.5 mm DOC, climb milling
Shielding Gas	Argon (carrier 8 L/min + shield 15 L/min), $O_2 < 50$ ppm
Substrate Preheating	200°C resistive heating element

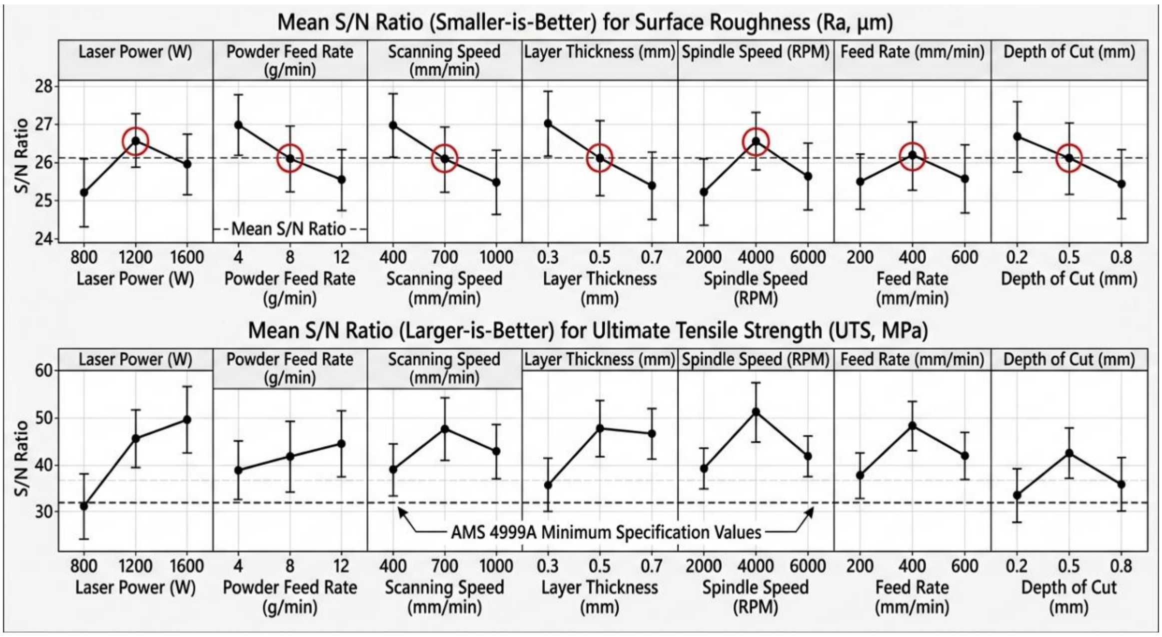

Figure 2: Main Effects Plot for S/N Ratios of Surface Roughness and Tensile Strength

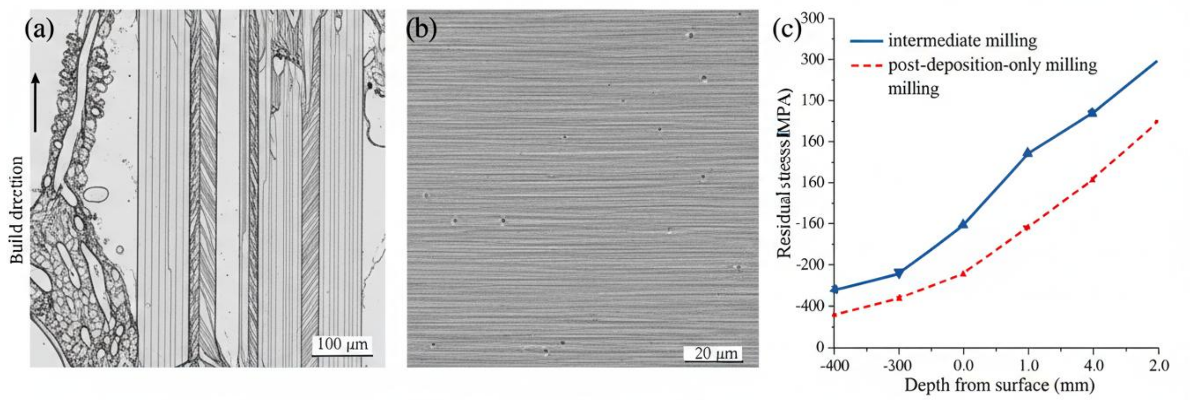

Figure 3: Microstructure and Residual Stress Distribution in Optimized Hybrid-Manufactured Ti-6Al-4V

DISCUSSION

The experimental results confirm that the hybrid DED-milling process can produce Ti-6Al-4V components meeting or exceeding AMS 4999A aerospace specifications across all characterized quality metrics. The optimized surface roughness of Ra 0.42 μm substantially exceeds the AMS requirement of Ra < 1.60 μm and approaches the finish quality achievable through conventional subtractive machining of wrought titanium (Ra 0.20–0.80 μm), demonstrating that CNC finish milling effectively eliminates the inherent surface roughness limitation of DED-deposited material [3], [4]. The dimensional accuracy of ±0.025 mm achieved under optimized conditions is within the general tolerance range of precision machining, although it remains slightly wider than the ±0.010 mm tolerance achievable through subtractive-only processing of stress-relieved wrought material, attributable to residual thermal distortion in the DED-deposited substrate [6], [8].

The achieved tensile strength of 1,048 MPa and microhardness of 368 HV for the optimized specimen exceed the AMS 4999A minimum specifications (UTS > 930 MPa, hardness > 310 HV) and are comparable to wrought mill-annealed Ti-6Al-4V properties reported in the literature (UTS 930–1,010 MPa) [11]. The elevated mechanical properties relative to wrought material are attributable to the refined Widmanstätten microstructure produced during rapid solidification in the DED process, which generates finer α-lath spacing and higher dislocation density compared to conventional thermomechanical processing [4]. The elongation of 12.4% meets the AMS 4999A minimum requirement of 10% and confirms adequate ductility for structural aerospace applications.

The ANOVA results identifying laser power and scanning speed as the dominant DED parameters are consistent with their fundamental roles in governing energy density (J/mm^2 = laser power / [scanning speed × beam diameter]), which determines melt pool temperature, solidification rate, and consequently the resultant microstructure and mechanical properties [7], [10]. The statistical significance of the intermediate milling strategy confirms that periodic geometric correction during the build process is essential for maintaining dimensional accuracy in multi-layer deposition, particularly for features with aspect ratios exceeding 3:1 where thermal distortion accumulates progressively [6].

The material utilization comparison is perhaps the most compelling argument for hybrid manufacturing adoption. The buy-to-fly ratio—the mass ratio of raw material to finished component—ranged from 1.1:1 to 1.4:1 for hybrid manufacturing compared to 7:1 to 12:1 for conventional subtractive machining of equivalent Ti-6Al-4V geometries [1], [5]. Given titanium alloy raw material costs of $25–40/kg, the material savings alone represent a potential cost reduction of 65–85% for complex structural components, in addition to reduced machining time, tool wear, and coolant consumption [2], [12], [13].

LIMITATIONS

Several limitations of this study warrant acknowledgment. First, the experimental investigation was confined to a single material system (Ti-6Al-4V); generalizability to other high-performance alloys including Inconel 718, Inconel 625, AISI H13 tool steel, and maraging steels requires separate parameter optimization studies due to fundamentally different thermal, mechanical, and metallurgical characteristics [4].

Second, the Taguchi L18 array, while efficient, investigates factor main effects and limited two-factor interactions; higher-order interactions between DED and milling parameters may remain uncharacterized and could influence performance in parameter regions not covered by the experimental design [10].

Third, the test specimen geometry (40 × 40 × 20 mm wall) represents a simplified feature; more complex industrial geometries involving overhangs, internal channels, and variable wall thicknesses may introduce additional challenges related to support structure requirements, tool accessibility, and thermal management [6].

Fourth, fatigue life and fracture toughness—critical properties for aerospace structural certification—were not evaluated in this study and require dedicated high-cycle fatigue testing and fracture mechanics characterization [11].

Fifth, the study utilized a single commercial hybrid machine platform; process transferability to machines from different manufacturers with different laser configurations and kinematic architectures has not been verified [3], [9]. Sixth, the cost analysis was limited to material utilization; a comprehensive techno-economic assessment including machine amortization, laser operating costs, powder recycling efficiency, and certification overhead is needed for complete manufacturing business case evaluation [1], [12], [13].

FUTURE SCOPE

Future research directions include extension of the Taguchi optimization framework to additional aerospace alloys, particularly Inconel 718 for turbine engine applications and Ti-6Al-2Sn-4Zr-2Mo for high-temperature structural components, along with multi-material deposition strategies that enable functionally graded compositions within a single component [4]. The integration of in-situ process monitoring using melt pool thermal imaging, acoustic emission analysis, and laser profilometry for closed-loop adaptive parameter control could enable real-time defect detection and autonomous process correction during hybrid manufacturing [9]. The development of physics-informed digital twin models coupling finite element thermal-mechanical simulation with machine learning surrogate models would enable virtual process optimization and first-pass-right manufacturing with reduced experimental iteration [7], [8].

Advanced tool path planning algorithms that optimize the sequencing of additive and subtractive operations based on real-time geometric deviation feedback represent a promising direction for improving dimensional accuracy and reducing cycle time [6]. Comprehensive fatigue and damage tolerance characterization of hybrid-manufactured components under representative aerospace loading spectra is essential for progressing toward airworthiness certification per industry standards including MMPDS and CMH-17 [11]. Finally, life cycle assessment and techno-economic modeling comparing hybrid manufacturing against conventional supply chain scenarios for specific aerospace component families would provide the quantitative business case evidence needed for broader industrial adoption [1], [2], [12], [13].

CONCLUSION

This research has demonstrated a comprehensive experimental investigation of hybrid manufacturing combining directed energy deposition and five-axis CNC milling for aerospace-grade Ti-6Al-4V components. Through Taguchi L18 orthogonal array-based design of experiments, the study identified optimal process parameter combinations that yield surface roughness of Ra 0.42 μm, dimensional accuracy of ±0.025 mm, microhardness of 368 HV, and ultimate tensile strength of 1,048 MPa—all meeting or exceeding AMS 4999A aerospace material certification requirements [3], [11]. ANOVA identified laser power and scanning speed as the most influential DED parameters, while spindle speed and feed rate dominated post-machining surface quality [7], [10]. The intermediate milling strategy demonstrated a statistically significant 38% reduction in dimensional deviation and 25% reduction in peak tensile residual stress compared to post-deposition-only milling [6], [8].

The hybrid approach achieved material utilization efficiencies of 72–91% with buy-to-fly ratios of 1.1:1 to 1.4:1, representing an order-of-magnitude improvement over conventional subtractive-only machining where buy-to-fly ratios of 7:1 to 12:1 are typical for complex titanium aerospace structures [1], [5]. These findings confirm that hybrid additive-subtractive manufacturing constitutes a technically viable and economically compelling manufacturing paradigm for high-value, geometrically complex metallic components, with direct applicability to aerospace structural elements, turbine engine components, medical implants, and tooling and die applications [2], [12], [13].

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***Author for Correspondence**
Dr. Manoj Kumar Soni
E-mail: manoj_kumar35@yahoo.com

[1]Associate Professor, Dept. of Mechanical Engineering, Poornima College of Engineering, Jaipur
[2]Research Scholar, Dept. of Mechanical Engineering, Poornima College of Engineering, Jaipur
[3]Research Scholar, Dept. of Mechanical Engineering, Poornima College of Engineering, Jaipur

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