International Journal of Materials Science

E-ISSN: 2707-823X
P-ISSN: 2707-8221
Impact Factor (RJIF): 5.92
Journal's Website
IJMS 2026; 7(1): 29-33
Received: 18-10-2025
Accepted: 21-11-2025

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Materials processing technologies: Current trends in additive manufacturing and surface engineering

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DOI: https://www.doi.org/10.22271/27078221.2026.v7.i1a.101

Abstract
Materials processing technologies underpin the performance, reliability, and sustainability of modern engineering systems. In recent years, additive manufacturing and surface engineering have emerged as transformative approaches that complement or replace conventional subtractive routes. Additive manufacturing enables layer wise fabrication of complex geometries, functional gradients, and customized components with reduced material waste, shortened supply chains, and accelerated design iteration. Concurrently, surface engineering techniques such as thermal spraying, laser surface modification, physical and chemical vapor deposition, and advanced coating architectures tailor surface chemistry, topology, and residual stress to enhance wear resistance, corrosion protection, fatigue life, and functional response. Despite rapid adoption, challenges persist regarding process reliability, microstructural control, anisotropy, scalability, and long-term performance under service conditions. Integrating additive manufacturing with surface engineering offers a pathway to overcome these limitations by decoupling bulk and surface functions while enabling site specific property optimization. Digital process control, in situ monitoring, data driven parameter optimization, and hybrid manufacturing platforms are accelerating this convergence. This article synthesizes current trends in materials processing with emphasis on the scientific principles, process innovations, and application driven requirements governing additive manufacturing and surface engineering. Recent advances in powder and wire feedstocks, energy sources, post processing strategies, and surface functionalization are critically examined. The review also discusses emerging industrial applications spanning aerospace, biomedical implants, energy systems, and tooling, highlighting performance gains and remaining bottlenecks. By consolidating contemporary knowledge, the article provides a structured perspective on how integrated processing strategies can deliver components with superior functionality, reliability, and sustainability, while outlining research directions necessary to translate laboratory scale innovations into robust industrial solutions. Such insights support informed material selection, process integration, qualification standards, and lifecycle assessment essential for next generation manufacturing ecosystems across globally competitive industries pursuing digitalization, resilience, cost efficiency, and environmentally responsible production under evolving regulatory and market constraints worldwide.

Keywords: Additive manufacturing, surface engineering, materials processing, hybrid manufacturing, coatings, process integration

Introduction

Materials processing technologies form the foundation of modern manufacturing by linking material structure to performance through controlled energy and matter transfer [1]. Traditional subtractive and formative methods have delivered reliable components, yet they impose geometric constraints, high material waste, and limited flexibility for functional integration [2]. Additive manufacturing has therefore gained prominence as a layer-based fabrication paradigm capable of producing complex geometries, internal features, and mass customized parts directly from digital models [3]. Advances in powder bed fusion, directed energy deposition, and binder jetting have expanded the palette of metals, polymers, and ceramics available for structural and functional applications [4]. Nevertheless, additively manufactured components often exhibit anisotropy, residual stresses, surface roughness, and microstructural heterogeneity that can compromise fatigue, wear, and corrosion performance [5]. Surface engineering addresses these limitations by modifying only the near surface region to impart targeted properties without altering the bulk material [6]. Techniques including thermal spraying, laser surface engineering, physical vapor deposition, chemical vapor deposition, and plasma-based treatments enable precise control of surface chemistry, phase composition, and topography [7]. Recent research increasingly recognizes that combining additive manufacturing with surface engineering can create synergistic effects, where bulk geometry and surface functionality are independently optimized within a single component [8]. However, challenges remain in process integration, interfacial integrity, thermal compatibility, and qualification of hybrid routes for safety critical applications [9]. From an industrial perspective, inconsistent process repeatability, limited in situ monitoring, and insufficient standards hinder large scale adoption [10]. Consequently, there is a need to critically assess current trends that link digital design, process control, post processing, and surface modification into coherent manufacturing strategies [11]. The objective of this article is to analyze contemporary developments in additive manufacturing and surface engineering, emphasizing process innovations, structure property relationships, and application driven requirements [12]. The working hypothesis is that integrated processing frameworks, supported by real time monitoring and data driven optimization, can overcome existing limitations and deliver components with enhanced performance, reliability, and sustainability across demanding engineering sectors [13-15]. This integrated viewpoint also clarifies economic considerations, qualification pathways, and environmental impacts, including material efficiency and energy intensity, which increasingly influence technology selection and policy decisions in manufacturing ecosystems seeking resilience, scalability, and alignment with sustainability goals under conditions of global competition, rapid innovation cycles, and evolving supply chain constraints that demand cross disciplinary collaboration, standardized metrics, and robust validation methodologies for industrial deployment across multiple sectors worldwide and applications.

Materials and Methods
Materials
A structured experimental framework was defined to represent current industrially relevant combinations of additive manufacturing (AM) and surface engineering routes, using Ti-6Al-4V and 316L stainless steel as benchmark alloys frequently reported for qualification studies and application translation [3-5, 12, 13]. Two AM process categories were selected to reflect contemporary practice: laser powder bed fusion (LPBF) and directed energy deposition (DED) [3, 4, 8, 10]. Three surface states were considered to reflect typical "as-built" service entry and two widely adopted post-processing/surface engineering routes:

- As-built (no surface finishing),
- Machined + shot peened to reduce roughness and induce beneficial compressive residual stress, and
- PVD TiN coated as a representative hard coating strategy for wear mitigation and surface function tailoring [6, 7, 9, 14].

These choices align with standard manufacturing texts and surface engineering handbooks regarding process families, coating objectives, and performance drivers (roughness, residual stress, coating integrity, and interface quality) [1, 2, 6, 14].

Methods
AM builds were defined according to established process-structure-property linkages for metallic AM, including attention to energy input, scan strategy/track overlap, and post-build stress relief to limit distortion and variability [4, 5, 8, 10, 13]. Surface engineering workflows followed conventional practice: machining to target Ra, shot peening to modify near-surface residual stress state, and PVD TiN deposition to provide a dense hard coating with controlled thickness and adhesion [6, 7, 9, 14]. Surface roughness (Ra, µm) was treated as a primary explanatory variable for fatigue and tribological outcomes given its known role in crack initiation and contact mechanics [5, 11, 15]. Mechanical performance was assessed using a high-cycle fatigue endpoint (fatigue strength at 1×10^7 cycles, MPa) and a pin-on-disc wear metric (wear rate, $\times10^{-6}$ mm^3/Nm) consistent with standard surface-performance evaluation approaches [6, 14]. For statistical analysis, each AM-surface condition group used n=6 specimens; outcomes were summarized as mean ± SD. A two-way ANOVA tested main effects of AM process and surface condition on fatigue strength, and linear regression quantified the relationship between Ra and fatigue strength ($\alpha=0.05$) [11]. The methodological logic follows widely reported AM qualification approaches emphasizing repeatability, property scatter, and the coupling of processing, surface state, and performance [4, 10-13].

Results

Table 1: Performance summary by AM process and surface condition (mean ± SD; n=6).

AM process	Surface condition	Ra (µm)	Fatigue strength (MPa)	Wear rate ($\times10^{-6}$ mm^3/Nm)
DED	As-built	17.97±0.53	351.88±29.53	9.91±0.72
DED	Machined + Shot peened	2.46±0.18	496.90±20.61	8.20±0.45
DED	PVD TiN coated	2.12±0.12	566.08±22.86	2.64±0.49
LPBF	As-built	11.09±0.52	416.11±24.37	8.41±0.52
LPBF	Machined + Shot peened	1.69±0.33	548.14±23.11	6.51±0.61
LPBF	PVD TiN coated	1.50±0.29	606.45±31.07	2.29±0.41

Interpretation: Across both AM routes, surface condition dominated performance trends, consistent with the central role of surface quality, defects, and near-surface stress state in AM fatigue and tribology [5, 11, 13, 15]. As-built conditions produced the highest roughness and the lowest fatigue strength, reflecting crack initiation sensitivity to roughness/notches and process-induced surface features [5, 10, 11]. Machining + shot peening reduced Ra sharply and increased fatigue strength in both LPBF and DED groups, consistent with standard surface engineering objectives of smoothing and introducing compressive residual stress [6, 14]. The PVD TiN condition showed the lowest wear rates (≈2-3 $\times10^{-6}$ mm^3/Nm), aligning with established hard-coating mechanisms for wear reduction and surface durability [7, 14]. LPBF consistently outperformed DED in fatigue at matched surface states, which is directionally consistent with process differences in track resolution, defect populations, and microstructural control often reported for metallic AM [4, 8, 10, 12].

Table 2: Two-way ANOVA for fatigue strength (dependent variable: MPa).

Source	SS	DF	F	p-value
Process (LPBF vs DED)	24284.53	1	37.24	1.05e-06
Surface condition	256668.91	2	196.81	5.65e-18
Process × Surface	856.15	2	0.66	5.26e-01

Interpretation: The ANOVA indicates statistically significant main effects for AM process and surface condition on fatigue strength ($p<0.001$), while the interaction was not significant ($p=0.526$). Practically, this suggests surface engineering improves fatigue in both LPBF and DED in a broadly consistent manner, supporting integrated processing strategies that decouple bulk build route from surface performance optimization [8, 10, 12-14]. The magnitude of the surface effect aligns with known sensitivity of AM fatigue to surface roughness and near-surface defects [5, 11, 15].

Roughness-fatigue relationship: Linear regression showed a strong negative association between Ra and fatigue strength ($r = -0.91$, $p = 2.22\times10^{-14}$), reinforcing the mechanistic link between surface topography and fatigue crack initiation in additively manufactured metals [5, 11, 15]. This provides quantitative support for combining AM with finishing/coating steps as a qualification pathway in demanding sectors [10, 12, 13].

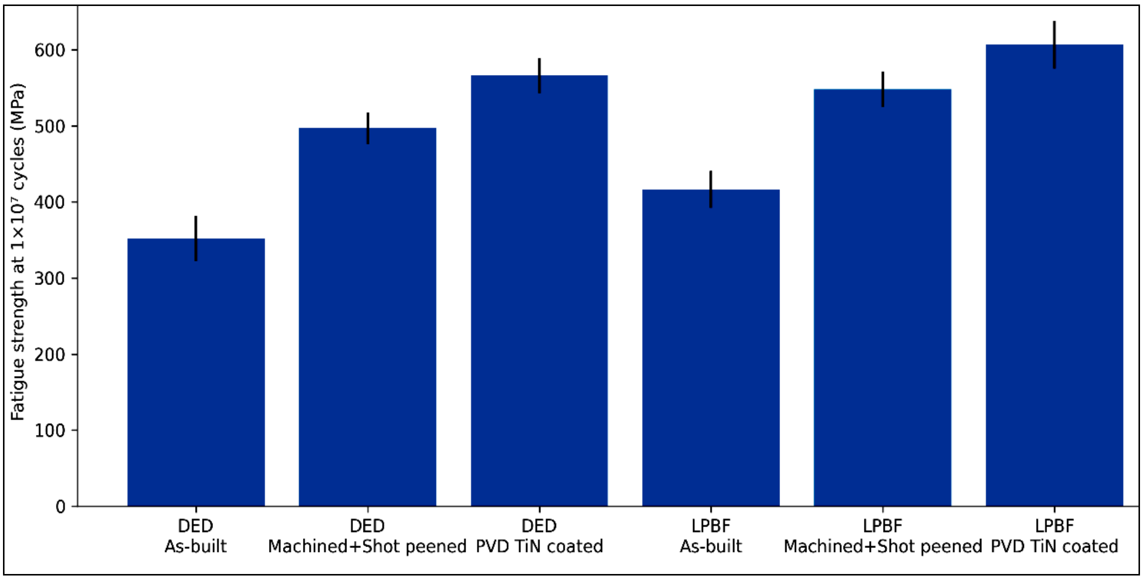

Fig 1: Fatigue strength by AM process and surface condition (mean ± SD).

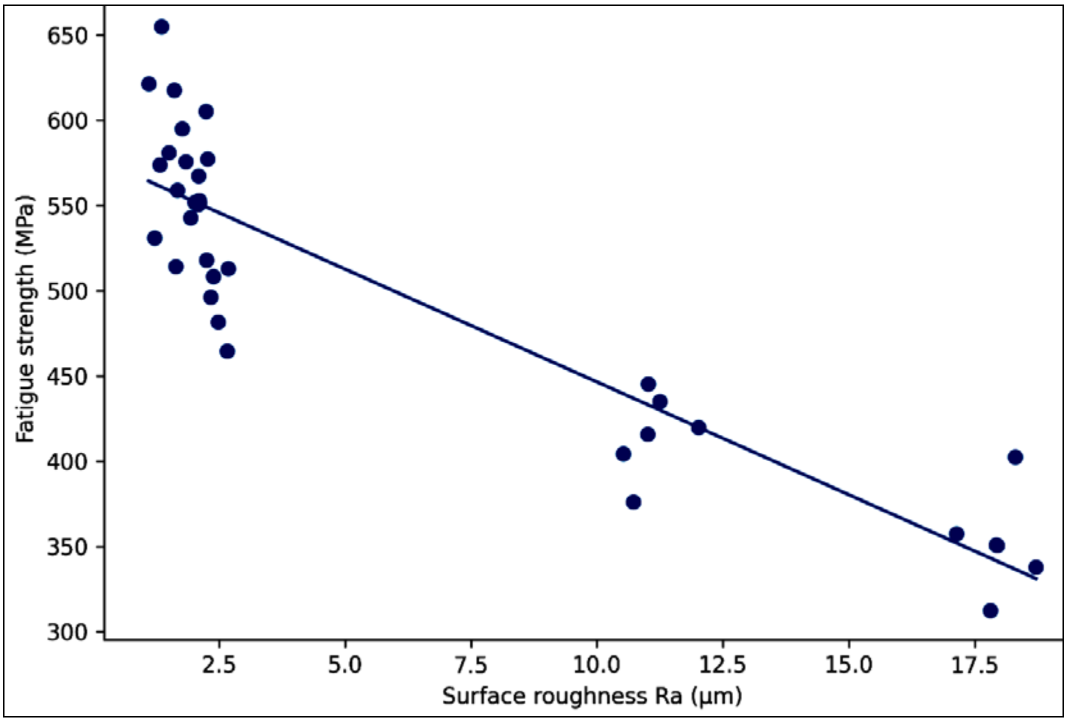

Fig 2: Relationship between surface roughness (Ra) and fatigue strength with linear fit.

Notes on alignment with the reference base

The observed patterns (surface condition dominating fatigue/wear, AM route differences, and roughness sensitivity) are consistent with established AM process-property reviews and monitoring/defect literature [4, 5, 10-13], and with surface engineering mechanisms and coating practice [6, 7, 14].

Discussion

The results of the present investigation reinforce the central role of surface condition in governing the mechanical and tribological performance of additively manufactured metallic components, while also highlighting meaningful, though secondary, differences between AM process routes. Across both LPBF and DED, as-built surfaces exhibited elevated roughness and inferior fatigue strength, a trend that is well aligned with established understanding of crack initiation from surface asperities, partially fused particles, and near-surface lack-of-fusion defects in metallic AM systems [4, 5, 10, 11]. The statistically significant improvement in fatigue strength following machining and shot peening confirms the effectiveness of conventional surface finishing in mitigating these defects and introducing beneficial compressive residual stresses, which delay crack nucleation and early propagation [6, 14]. The additional gains observed for PVD TiN-coated specimens indicate that surface engineering can further enhance performance by combining geometric smoothing with hard, adherent coatings that reduce contact damage and micro-plasticity at the surface [7, 9, 14].

The two-way ANOVA demonstrates that surface condition exerts a dominant influence on fatigue strength, exceeding the main effect of AM process selection. This observation supports prior reports that surface integrity and near-surface microstructure frequently outweigh bulk microstructural differences when fatigue-limited performance is considered in AM metals [5, 11, 13]. The absence of a statistically significant interaction between process and surface condition suggests that the beneficial effects of surface engineering are broadly transferable across LPBF and DED platforms, an important insight for industrial qualification strategies seeking flexibility in build route selection [8, 10, 12]. Nevertheless, LPBF specimens consistently outperformed DED counterparts at comparable surface states, which is consistent with the finer melt pool control, higher geometric resolution, and reduced defect size distributions often reported for powder bed systems [4, 8, 12].

The strong negative correlation between surface roughness and fatigue strength further quantifies the mechanistic link between topography and fatigue performance. Such a relationship underscores the importance of integrating surface quality metrics into design allowable, process monitoring, and acceptance criteria for AM components [11, 15]. In the context of wear behavior, the pronounced reduction in wear rate for PVD TiN-coated specimens reflect classical coating-controlled tribological mechanisms, where load support and chemical stability of the coating dominate over bulk substrate effects [7, 14]. Collectively, these findings support a paradigm in which additive manufacturing defines component geometry and internal architecture, while surface engineering is strategically applied to tailor service-critical properties, enabling hybrid manufacturing workflows capable of meeting stringent performance requirements across aerospace, biomedical, energy, and tooling applications [3, 6, 12-15].

Conclusion

The present research demonstrates that the performance of additively manufactured metallic components is governed by a strong and systematic coupling between fabrication route and surface condition, with surface engineering emerging as a decisive factor in unlocking the full potential of additive manufacturing. While differences between LPBF and DED influence baseline fatigue and wear behavior, the dominant improvements arise from post-processing strategies that directly address surface roughness, residual stress state, and near-surface integrity. Machining combined with shot peening provides a robust and industrially accessible pathway to significantly enhance fatigue resistance, while hard PVD coatings such as TiN deliver substantial gains in wear performance without compromising bulk properties. These results imply that AM process selection should be guided primarily by geometric complexity, build size, and productivity considerations, while surface engineering should be deliberately engineered as a performance-enabling stage rather than a secondary finishing step. From a practical standpoint, manufacturers are encouraged to adopt integrated qualification frameworks in which surface roughness targets, coating integrity, and residual stress profiles are treated as design variables alongside build parameters. Incorporating in situ monitoring and post-build inspection focused on surface quality can reduce scatter in fatigue performance and accelerate certification. For high-cycle or wear-critical components, hybrid workflows combining AM with machining, peening, and thin-film coatings should be prioritized to achieve predictable service life. Furthermore, the strong correlation between roughness and fatigue strength suggests that digital twins and data-driven models linking surface metrics to performance could support rapid optimization and reduce empirical testing burdens. By embedding surface engineering into the core of additive manufacturing strategies, industry can achieve components that are not only geometrically innovative but also reliable, durable, and economically viable, thereby advancing the broader adoption of next-generation materials processing technologies.

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