International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(20s) 2026 pp. 923-934
https://doi.org/10.70917/ijcisim-2026-5229
Article

Comparing Additive and Subtractive Manufacturing: An Evaluation Across Seven Criteria

Lavanya Rai

Dhirubhai Ambani International School, Mumbai (India)
lavanyalrai@gmail.com

Abstract: Additive Manufacturing (AM) and Subtractive Manufacturing (SM) build parts by opposite mechanisms: AM adds material layer by layer, most commonly through 3D printing, while SM removes material from a solid block until the required shape remains. Although the two are frequently framed as competitors, they are largely complementary, each better suited to different classes of parts. This paper undertakes a structured, literature-based comparison of AM and SM across seven criteria: material utilization, surface finish and dimensional accuracy, mechanical properties, production cost, production time, environmental sustainability, and industrial application. To isolate the effect of process from the effect of material, one material is held fixed for each method: Ti-6Al-4V produced by Direct Metal Laser Sintering (DMLS) for AM, and 316L austenitic stainless steel machined by Computer Numerical Control (CNC) for SM. Synthesizing findings from recent published research, the analysis shows that neither method is superior across all criteria; rather, the preferred choice depends primarily on production volume, geometric complexity, required tolerance, and material cost. The comparison further indicates that, in current industrial practice, the strongest outcomes often arise not from selecting a single method but from combining both within the same production workflow.
Keywords: Additive manufacturing, subtractive manufacturing, 3D printing, CNC machining, material utilization, surface roughness, mechanical properties, production cost, sustainability, Ti-6Al-4V, 316L stainless steel

1. INTRODUCTION

Almost every manufactured object has to be shaped from raw material, and for most of the last century that meant cutting a larger block down until the required form was left. This removal-based approach, called Subtractive Manufacturing (SM), became fully industrial with Computer Numerical Control (CNC) machining, in which a cutting tool follows a programmed path with high precision and consistent repeatability [1], [2].

Over the past four decades a very different approach has appeared. Instead of removing material, Additive Manufacturing (AM), better known as 3D printing, builds a part by adding thin layers one after another according to a digital model [3]. It began in the 1980s as a way to make prototypes quickly, but it has since grown into a practical method for functional, end-use parts in demanding fields such as aerospace and biomedicine [4], [5].

Because both approaches are now available, engineers face a real choice. When a part could be made either way, the decision is rarely obvious, since each method does better on some measures and worse on others. Aerospace gives a clear example: a fuel nozzle with internal cooling passages is printed because no cutting tool can reach those passages, while a nearby structural fitting that needs tight tolerances is machined because additive accuracy alone is not enough [6], [7]. The choice therefore depends on several criteria at once, and the goal of this paper is to bring those criteria together into one clear comparison.

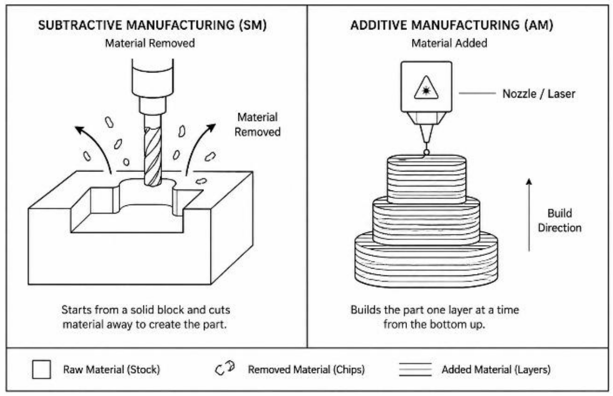

Fig. 1. Fundamental process distinction between additive and subtractive manufacturing.

The decision matters. Choosing the wrong process can produce a part that is too weak, too expensive, or impossible to

finish on time, and at industrial scale these mistakes are costly. For this reason the comparison deserves careful treatment, rather than the common assumption that AM, being newer, must be better. The real situation is more balanced, and making that balance clear is the main aim of this work.

To keep the comparison controlled, the paper uses seven criteria and fixes one material for each method. AM is represented by the titanium alloy Ti-6Al-4V made by DMLS, and SM by 316L stainless steel machined on CNC equipment. Because both alloys are used in similar industries, any difference that appears can be traced to the processes themselves rather than to a mismatch between materials. The rest of the paper is organized as follows. Section II explains how each method works and reviews related research; Section III describes the methodology; Section IV gives the criterion-by-criterion comparison, supported by two summary tables; Section V draws out the main findings; Section VI concludes; and Section VII looks at where the field is heading.

2. BACKGROUND AND RELATED RESEARCH

A. Additive Manufacturing

Additive Manufacturing is not a single technique but a family of processes that share one basic idea: a part is built up layer by layer from a digital model [3], [41]. The first process, stereolithography, was developed by Chuck Hull in the 1980s and cured liquid resin with ultraviolet light one layer at a time [4]. Many variants have appeared since, differing mainly in their feedstock and in how each layer is joined. Material-extrusion processes melt and lay down thermoplastic through a nozzle, while powder-bed fusion processes such as DMLS and Electron Beam Melting use a laser or electron beam to fuse metal powder into fully dense, load-bearing parts [3], [5], [31].

Because material is placed only where the design needs it, AM can create shapes that ordinary machining cannot, including hollow interiors, internal lattices, and conformal cooling channels that follow the shape of the part [5], [8]. Since no part-specific tooling is required, making a single custom part is fast and fairly cheap [9]. These abilities have taken AM well beyond prototyping. Aerospace manufacturers now print lightweight, topology-optimized brackets and fuel parts, sometimes combining a twenty-piece welded assembly into one printed part, which cuts both weight and the number of possible failure points [8], [10], [11], [42]. In medicine, AM makes patient-specific implants whose internal porosity can be tuned to match the stiffness of bone [12].

This change in thinking is more important than it first seems. For almost all of manufacturing history, making a part started with more material than needed. AM reverses that idea completely, and this reversal is what gives the technology its main strength: the ability to make shapes that were once impractical or impossible. It is this design freedom, more than any gain in speed or cost, that explains much of the attention AM has received [5], [8].

The method also has well-known limits. Build rates are low compared with machining, which holds AM back in high-volume production [6], [13]. The layer-by-layer build leaves as-built surfaces fairly rough, so a finishing step is usually needed [14]. Mechanical properties are often anisotropic, meaning they change with build direction, which makes design and qualification harder [5], [15]. Finally, the fast heating and cooling in metal AM create residual stresses and porosity that can lower fatigue life unless they are relieved by post-processing such as hot isostatic pressing [13], [16].

B. Subtractive Manufacturing

Subtractive Manufacturing makes a finished part by cutting material away from a larger block [1]. Material has been shaped this way for centuries, but modern CNC machines automate the work, following a programmed path that can be repeated accurately across thousands of parts [2]. The family includes turning, milling, drilling, and grinding, and milling is the operation most often compared with AM [17].

The main strength of SM is dimensional accuracy and surface quality. A well-set-up CNC machine can hold tolerances of about ±10 μm and produce surfaces smooth enough to be used directly as sealing or bearing faces, with no extra finishing [2], [17]. This precision comes from how the process works: because the part is cut from stable, fully solid stock, the final shape is set by the controlled motion of the tool rather than by the less predictable joining of feedstock. A second strength is material integrity. Because the part comes from certified wrought stock, its mechanical properties are already known and reliable, which is essential in industries that require full traceability [18].

The main drawback of SM is waste. Since shaping happens by removal, all the material cut away becomes scrap, usually called chips. For complex parts made from expensive alloys this waste is large; in some aerospace parts the buy-to-fly ratio, the mass of purchased stock compared with the finished part, reaches as high as twenty to one [19]. Recycling reduces this loss, since metal chips are routinely collected and remelted into new stock [20]. SM also needs tooling and setup before the first part is made, which is slow and costly for small runs, but once setup is done each extra part is fast and cheap, which keeps machining dominant for high-volume production [2], [17].

None of this makes machining outdated. Its accuracy, speed at volume, and reliable material properties keep it central to industry, and for many ordinary parts it is still the obvious and cheapest option. A better way to see it is not old versus new, but two different toolsets, each suited to a particular kind of work [2], [17].

C. Related Research

The literature comparing AM and SM converges on three recurring themes. Sustainability studies consistently find that neither method is inherently greener: the outcome depends on part geometry and production volume, with AM generally favoured for complex, low-volume parts and SM for large, simple ones [20]. A second theme concerns surface integrity, where researchers have quantified the roughness of as-built additive parts and shown that post-processing can recover most of the gap relative to machined surfaces [14]. A third theme is economic modelling: break-even studies identify the production volume at which the cost advantage shifts from one method to the other, giving the comparison a quantitative basis rather than relying on general impression [9], [21].

A separate and rapidly growing strand of research examines combining the two methods within a single machine, motivated by the observation that the limitations of one process are frequently offset by the strengths of the other [22], [23], [45]. This combined approach is particularly valuable for repairing high-value metal components, a task pure machining cannot perform because it cannot add material back onto a worn part [7], [25], [47]. Commercial machines capable of both depositing and machining material already exist, and research output on the topic continues to expand [24], [26], [40]. Although this paper concentrates on the two pure processes, it returns to the combined approach in the discussion of future directions, since integration appears to be the field's clearest trajectory. Notably, independent research groups working with different methodologies converge on the same broad conclusion, that no single process is universally best and that the appropriate choice depends on the part, which lends that conclusion considerable weight [20], [26], [50].

Several of these studies offer sufficiently granular results to anchor a quantitative comparison. In surface finishing, researchers have measured the roughness reduction achieved by specific treatments, with polishing and laser processing shown to lower roughness substantially. In cost analysis, break-even models estimate the approximate volume at which machining becomes cheaper than printing. Findings of this kind allow a comparison such as the present one to rest on measured evidence rather than general impression [14], [21]. What remains comparatively rare in the literature, however, is a single synthesis that brings these separate strands of evidence, on utilization, finish, mechanical behaviour, cost, time, sustainability, and application, together under one consistent framework and a matched pair of materials. The present study addresses that gap by organizing published results from across these strands into the seven-criterion comparison described in Section III.

3. METHODOLOGY

A. Approach

This study does not run new experiments. Instead, it brings together results already published in the literature and organizes them into one structured comparison. The seven criteria were chosen in advance, each method was assessed on its own against every criterion, and the two were then compared directly. This kind of secondary-research design is normal for a review of this size, where full laboratory access is not available [20], [21]. Where a source gives a range of values rather than a single number, the range is kept, so the comparison does not claim more precision than the evidence supports.

B. Material Selection

One material was fixed for each method to keep the comparison controlled. Ti-6Al-4V was chosen for AM because it is the main metal feedstock in aerospace and biomedical printing and is very well studied in the literature [10], [12], [15]. 316L stainless steel was chosen for SM because it is one of the most widely machined alloys and is also the most common metal in the combined additive-subtractive literature, which makes cross-referencing easier [18], [26], [33]. Because both materials are used in similar applications, the comparison separates the effect of the process from the effect of the material.

C. Evaluation Criteria

Each criterion has a clear meaning. Material utilization is the share of purchased material that ends up in the finished part, often given as a buy-to-fly ratio. Surface finish and dimensional accuracy describe how smooth the surface is, measured as roughness, and how closely the part matches its intended size, measured as tolerance. Mechanical properties cover strength, ductility, hardness, and whether behaviour is the same in all directions. Production cost combines material, machine time, tooling, and labour, and changes with quantity. Production time is the interval from a finished design to a usable part. Environmental sustainability covers energy use, the amount and recoverability of waste, and hazardous by-products. Industrial application brings the first six together to show where each method is actually used.

D. Limitations

Three limitations should be stated. First, because the study uses published figures, the values are general trends rather than exact measurements and will change with the machine and its settings [20]. Second, AM and SM each include many sub-processes, so the conclusions describe the general behaviour of each family through its two chosen examples, not every variant. Third, only one material is studied per method, so applying the results to other materials should be done with care.

4. COMPARISON

This section looks at the seven criteria one by one. Table I gives a summary, and the discussion that follows develops each criterion in turn.

TABLE I . *SUMMARY COMPARISON OF ADDITIVE (TI-6AL-4V, DMLS) AND SUBTRACTIVE (316L, CNC) MANUFACTURING*

Criterion	Additive (Ti-6Al-4V, DMLS)	Subtractive (316L, CNC)
Material utilization	High; about 85 to 98% retained; leftover powder reusable	Lower; about 40 to 60% retained; chips recyclable
Surface and accuracy	Rougher as-built; needs finishing; tolerance about ±0.1 to 0.2 mm	Smooth as-machined; tolerance about ±0.005 to 0.05 mm
Mechanical properties	Very strong after heat treatment; can be anisotropic	Strong, isotropic, and certified
Production cost	Cheaper for one-offs; limited economies of scale	Costly setup; very cheap per part at volume
Production time	Fast setup, slow build (hours to days per part)	Slow setup, fast repeat parts
Sustainability	Less waste, but high build energy	More waste (recyclable), less energy, coolant disposal
Industrial application	Complex, custom, low-volume parts	High-volume, high-precision, certified parts

A. Material Utilization

Material utilization is the most intuitive point of contrast. In additive processing, material is added only where the geometry needs it, so waste is small. For Ti-6Al-4V made by DMLS, utilization is usually between 85 and 98 percent, and unfused powder can often be collected and reused [8], [29]. The benefit is greatest for expensive alloys such as titanium, where cutting waste leads directly to real cost savings [20], [37].

Subtractive processing works the opposite way, because removal is how the shape is made and scrap cannot be avoided. For a geometrically complex 316L part machined from billet, utilization drops to roughly 40 to 60 percent, and for some aerospace parts most of the block is removed [19]. Recycling reduces this drawback, since chips are collected and remelted into new stock [20]. On utilization, then, additive processing clearly leads, especially for complex shapes, while recycling narrows the gap for simple parts.

There is a wider point here. Material efficiency is not only about cost: producing raw metal causes a large share of manufacturing's environmental impact, so a method that wastes less also tends to start with a smaller footprint. This link comes up again in the sustainability section and is one of the strongest arguments for additive processing of expensive alloys [20], [37].

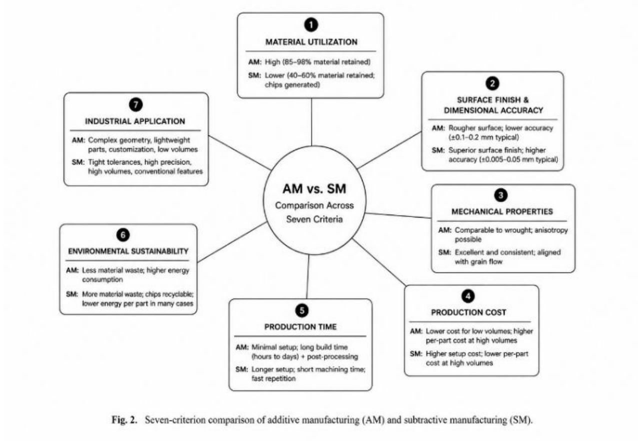

Fig. 2. Comparative evaluation of additive manufacturing (AM) and subtractive manufacturing (SM) across seven key criteria.

B. Surface Finish and Dimensional Accuracy

Surface finish and dimensional accuracy is the criterion where the two methods differ most, and here the subtractive advantage is clear. CNC machining of 316L reaches surface roughness of about 0.4 to 3.2 μm and tolerances as tight as ±5 μm, often giving surfaces ready for direct use without finishing [17], [28].

Additive surfaces show the mark of layer-by-layer building, a stepped texture known as the staircase effect [14]. A printed Ti-6Al-4V part is clearly rougher and less accurate, partly because the steep thermal gradients of the process cause distortion [16]. The gap is mostly recoverable, though: finishing methods such as vibratory abrasion and laser polishing cut roughness sharply, by 70 to 80 percent in some reports [14]. As a result, parts that must be both complex and precise are often printed close to their final shape and then machined on the critical surfaces [27].

It is easy to underestimate how much this criterion matters. Many parts have to seal against fluids, slide against other parts, or fit within very small clearances, and each of these depends directly on surface quality; a rough surface may leak, wear, or bind. This is why machining stays the default wherever a part has demanding functional surfaces, and why additive parts meant for these roles almost always get a finishing step [17], [27].

C. Mechanical Properties

Mechanical performance depends on the feedstock, on how the process changes it, and on any later treatment. In subtractive manufacturing the part is cut from solid wrought stock, and because machining does not change the bulk microstructure much, the finished properties closely match the certified input material. Wrought 316L has an ultimate tensile strength of about 485 to 620 MPa, stretches well before breaking, and is isotropic, meaning its properties are the same in all directions [18]. This predictability is valuable in itself, because it reduces the testing needed for qualification.

Additive processing is more complex, because the microstructure forms during the build and is sensitive to settings such as laser power, scan speed, and orientation [5], [15]. Ti-6Al-4V made by DMLS can reach an ultimate tensile strength of about 1000 to 1100 MPa, higher than 316L, but usually only after hot isostatic pressing closes internal porosity and relieves residual stress; in the as-built state, strength and ductility may be lower [15], [16]. Additive parts also tend to be anisotropic, while machined parts are isotropic and therefore easier to design around [5]. Recent combined processing has produced parts whose properties come close to machined stock [26], [33]; even so, residual stress and the immaturity of certification standards for additive metal are still the main reasons machining is preferred for safety-critical parts [16], [25].

What makes mechanical performance hard to generalize is that the additive result is not fixed. Two machines running the same design with different settings can give measurably different strength, while a machined part keeps the reliable properties of its stock almost unchanged. This variability is why additive parts usually need more testing before they can be trusted, and why heavily regulated industries have adopted them more slowly even when the measured strength is excellent [5], [15], [25].

D. Production Cost

Production cost combines material, machine operation, tooling, labour, and setup, and the mix changes a lot with volume. At low volumes, from a single prototype to batches of about ten, additive manufacturing is usually cheaper, because it needs neither part-specific tooling nor long setup; it starts with little more than a digital model and loaded feedstock [9], [21]. Subtractive manufacturing, by contrast, takes several hours of programming, fixturing, and tool setup before the first part is made, a fixed cost that does not depend on batch size [17].

As volume rises, the relationship flips. The fixed setup cost of machining is spread over many parts, so the per-part cost falls sharply, while each additive part uses a full build cycle and its cost falls only a little [21]. A single part costs thousands of dollars either way, but over hundreds or thousands of units a machined 316L part can drop to a few hundred dollars while a printed titanium part stays much higher. This volume-dependent crossover, the point where machining becomes cheaper, is the single most important factor when choosing on cost [9], [21]. Additive processing does save money in less obvious ways, such as combining several parts to remove assembly and producing locally to cut shipping, but the high purchase and running cost of additive systems still limits it at volume [9], [20], [40].

The cost picture also explains a common misconception. Additive manufacturing is sometimes assumed to be cheaper just because it is newer and looks more efficient, but that is only true at low volume. Once thousands of identical parts are needed, machining is usually far cheaper, and small improvements in printing do not change that math. Working out where a part falls on the volume scale answers the cost question faster than almost anything else [21].

E. Production Time

Production time includes setup, the build or machining, and post-processing. Additive setup is short, about 15 to 30 minutes, but the build itself is slow: a complex Ti-6Al-4V part may take 20 to 80 hours, plus more hours of finishing, giving total lead times of one to several weeks [13], [34]. For an equal part, metal printing is much slower than machining, which is the basic reason it cannot compete in mass production [17].

Subtractive lead time is mostly first-part setup, usually four to eight hours, after which a precise 316L part may be machined in well under an hour [17]. Importantly, each later part needs only loading and unloading, so a batch of fifty similar parts might be finished in about a week by machining but in several weeks by printing. A useful way to put it: printing front-loads little and then runs slowly, while machining front-loads a lot of setup and then runs quickly; the crossover in time, like the one in cost, depends on how many parts are needed [17], [34]. Smarter build strategies keep reducing additive build times, narrowing the gap without closing it [32], [35].

F. Environmental Sustainability

A fair environmental assessment goes beyond the workshop to energy use, hazardous by-products, and the full life cycle of the part [43]. Additive manufacturing is often called the greener option because of its high material efficiency, which matters because making raw metal is itself energy-intensive [20], [36]. That advantage is partly cancelled by the energy the process uses, since metal systems draw a lot of power during long builds, sometimes hundreds of kilowatt-hours per part [20], [38].

Subtractive manufacturing makes more waste, but the waste is recyclable, and per-part energy is generally lower. Its main environmental problem is cutting fluid, which contains chemical additives and needs controlled handling and disposal [20], [44]. The environmental ranking is therefore conditional. A frequently cited example involves polymer parts, where additive processing has the lower impact below about fourteen parts while injection moulding becomes better above about fifty, a clear volume-dependent crossover [30]. For titanium in particular, the high embodied energy of the raw metal means additive efficiency gives a real environmental benefit despite the higher build energy.

The broader lesson is to be careful with simple slogans. Sustainability depends on the whole picture, the material, the design, the production volume, and even the local energy source, not on the manufacturing method alone [51]. A given method may be the greener choice for one part and the worse choice for another, which is why careful comparisons tie the answer to a specific case rather than a blanket claim [20], [36], [38], [48].

G. Industrial Application

The industrial-application criterion brings the first six together. Additive manufacturing gives the most value where geometry is complex, parts are customized, volumes are low, or combining several parts into one saves money downstream. Typical cases include topology-optimized aerospace brackets, fuel parts with internal channels, patient-specific implants, and on-demand spares for old systems whose tooling no longer exists [8], [10], [11], [12], [39]. The main reason some firms stay cautious is a belief that additive processing is not yet precise or fast enough to replace machining [6].

Subtractive manufacturing stays the first choice wherever accuracy and finish are essential, volumes justify the setup, or certified properties are required. Typical applications include aerospace turbine parts, high-volume automotive powertrain parts, surgical instruments, and high-pressure valve bodies [2], [17], [18]. In each, exact dimensions and reliable properties are decisive.

Taken together, these examples make the same point in another form: each industry picks the method whose strengths match what its parts need, which is why one facility often runs both. The clearest trend is not one method replacing the other but the two being combined, with a near-net shape printed to save material and the critical surfaces then machined for precision [22], [25], [49]. This combined approach is especially good for repairing high-value parts, which machining alone cannot do, and commercial machines that do both operations in one setup already exist [24], [25], [40].

H. Synthesis

Because no single criterion decides things on its own, the right method for a given part comes from weighing several at once: geometric complexity, required tolerance, production volume, and material cost. Table II turns this into first-level guidance by matching common part types to the method that usually suits them, and marks a hybrid approach where neither pure method is enough [22], [24].

TABLE II. *RECOMMENDED METHOD BY APPLICATION CLASS*

Application Class	Recommended Method	Principal Reason
Complex aerospace parts	Additive	Internal channels and lattices; light-weighting; part consolidation
Aerospace structural and rotating parts	Subtractive	Tight tolerances and certified properties
Biomedical implants	Additive	Patient-specific geometry; bone-like porosity
Surgical instruments	Subtractive	Precision and certified, traceable properties
Automotive prototyping	Additive	Rapid iteration without tooling

Automotive powertrain (high volume)	Subtractive	Tight tolerances and low unit cost at scale
Tooling, dies and moulds	Hybrid	Conformal cooling channels; build-and-repair capability
Valves and flanges	Subtractive	High-pressure reliability; certified surfaces
Customized consumer goods	Additive	Small-batch personalization without tooling
Repair of high-value metal parts	Hybrid	Material can be added back, then machined to finish

Two patterns stand out. First, additive manufacturing fits low-volume, complex, or customized parts, while subtractive manufacturing fits high-volume, precise, certified parts, matching the criterion-level results above [20], [21]. Second, several of the hardest cases, such as tooling and the repair of expensive parts, fit neither pure method and are best served by combining them [22], [25]. This guidance is not a strict rule, since the underlying studies use different machines and metrics and there is no common benchmark, but it gives a solid starting point for process selection [32], [46].

5. KEY FINDINGS

Several findings come out of the comparison once the criteria are looked at together.

Finding 1. No single method is best in every case. The two approaches are not interchangeable, with one set to eventually win out. They occupy different performance ranges, and the right choice always depends on context [20], [22].

Finding 2. Production volume is the deciding economic factor. Below about fifty units, the lack of tooling makes additive manufacturing attractive; above that, the fast cycle time and spread-out setup of machining win. Because the same crossover shows up in the environmental comparison, volume often drives the decision more than any other factor [21], [30].

Finding 3. Additive leads on design freedom, subtractive on precision. Complex interiors, lattices, and topology-optimized shapes favour additive processing, while tight tolerances and smooth surfaces favour machining. This difference comes from how the two processes physically work, so it is unlikely to go away [5], [17].

Finding 4. The environmental advantage of additive manufacturing is real but conditional. Less material waste is a genuine benefit, especially for expensive alloys, but it is partly offset by higher build energy. The net result depends on material, energy source, and volume, so blanket claims are not justified [20], [36].

Finding 5. Mechanical properties are the most context-dependent criterion. Machined parts are predictable because they come from certified stock, while additive parts can match or beat them only with careful control and post-processing. The immaturity of additive certification standards is still a major barrier in safety-critical roles [15], [25].

Finding 6. Integration is the practical direction. Printing a near-net shape and then machining the critical surfaces captures the strengths of both, and is becoming standard in aerospace and biomedical work. It changes the main question from choosing one method to splitting the work between the two [24], [27], [40].

6. CONCLUSION

This paper set out to answer a practical question: when a part can be made by either additive or subtractive manufacturing, what should decide the choice? The seven-criterion comparison shows that the answer is rarely that one method is always better. Additive manufacturing is unmatched at making complex, customized shapes with high material efficiency, while subtractive manufacturing is unmatched at delivering precise, certified parts cheaply at scale.

All seven criteria point to the same conclusion. The better method depends on the part, mainly on its geometric complexity, the quantity needed, the required tolerance, and the cost of the material. For complex, low-volume parts, additive manufacturing wins; for precise, high-volume parts, subtractive manufacturing wins; and for parts that need both, the sensible response is to combine the two. The central question, then, is not which method is better in the abstract, but what a given part needs, in what quantity, and under what limits. Once those are clear, the right method usually follows.

If there is one habit of mind worth taking from this comparison, it is to resist looking for a single best method. Manufacturing rewards matching the process to the part, and the engineers who understand both approaches well are best placed to make that match. That mindset, rather than loyalty to any one technology, is what this comparison is meant to build.

7. FUTURE OUTLOOK

Both processes continue to evolve, and several ongoing developments are likely to reshape this comparison over time. Within additive manufacturing, multi-laser systems and improved in-process monitoring are gradually narrowing the disadvantages in build rate and process reliability, while maturing certification standards are expected to ease adoption in regulated sectors [5], [13]. Within subtractive manufacturing, advances in tool-path optimization and more efficient machining strategies continue to reduce waste and energy consumption, so the subtractive baseline is improving in parallel [18], [32].

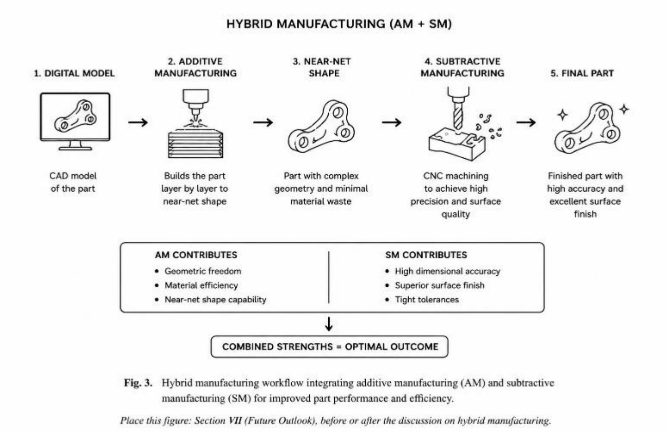

Fig. 3. Hybrid manufacturing workflow integrating additive manufacturing (AM) and subtractive manufacturing (SM) to produce complex, high-precision components.

The most consequential trend, however, is process integration. Machines that combine deposition and machining within a single workspace, without refixturing, are progressing from laboratory demonstration toward commercial production, and the volume of research on the topic continues to grow rapidly [24], [26], [40]. At present, such systems remain better suited to small-batch production and repair than to mass manufacturing, and coordinating the two operations still depends heavily on operator expertise [25], [40]. As these systems mature, the central engineering question is likely to shift from selecting between additive and subtractive manufacturing toward determining how best to combine them for a given part. In this sense, the comparative understanding developed in this paper, of where each method's strengths and limitations lie, provides the necessary foundation for the combined processes expected to define the next generation of manufacturing.

REFERENCES

1. M. P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 6th ed. Hoboken, NJ, USA: Wiley, 2020.
2. S. Kalpakjian and S. R. Schmid, Manufacturing Engineering and Technology, 7th ed. London, U.K.: Pearson, 2014.
3. I. Gibson, D. Rosen, and B. Stucker, Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, 2nd ed. New York, NY, USA: Springer, 2015.
4. S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: Scientific and technological challenges, market uptake and opportunities," Mater. Today, vol. 21, no. 1, pp. 22-37, 2018.
5. T. DebRoy et al., "Additive manufacturing of metallic components: Process, structure and properties," Prog. Mater. Sci., vol. 92, pp. 112-224, 2018.
6. M. Pérez, D. Carou, E. M. Rubio, and R. Teti, "Current advances in additive manufacturing," Procedia CIRP, vol. 88, pp. 439-444, 2020.
7. P. Stavropoulos, H. Bikas, O. Avram, A. Valente, and G. Chryssolouris, "Hybrid subtractive-additive manufacturing processes for high value-added metal components," Int. J. Adv. Manuf. Technol., vol. 111, pp. 645-655, 2020.
8. M. Seabra et al., "Selective laser melting (SLM) and topology optimization for lighter aerospace components," Procedia Struct. Integrity, vol. 1, pp. 289-296, 2016.
9. E. Atzeni and A. Salmi, "Economics of additive manufacturing for end-usable metal parts," Int. J. Adv. Manuf. Technol., vol. 62, no. 9, pp. 1147-1155, 2012.
10. T. Wohlers and T. Gornet, Wohlers Report: 3D Printing and Additive Manufacturing State of the Industry. Fort Collins, CO, USA: Wohlers Assoc., 2022.
11. S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: A literature review," Int. J. Adv. Manuf. Technol., vol. 67, no. 5-8, pp. 1191-1203, 2013.
12. L. E. Murr, S. M. Gaytan, E. Martinez, F. Medina, and R. B. Wicker, "Next generation orthopaedic implants by additive manufacturing using electron beam melting," Int. J. Biomater., vol. 2012, Art. no. 245727, 2012.
13. W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff, and S. S. Babu, "The metallurgy and processing science of metal additive manufacturing," Int. Mater. Rev., vol. 61, no. 5, pp. 315-360, 2016.
14. N. N. Kumbhar and A. V. Mulay, "Post processing methods used to improve surface finish of products manufactured by additive manufacturing technologies: A review," J. Inst. Eng. (India) C, vol. 99, no. 4, pp. 481-487, 2018.
15. A. Alafaghani and A. Qattawi, "Investigating the effect of fused deposition modeling processing parameters using Taguchi design of experiment method," J. Manuf. Processes, vol. 36, pp. 164-174, 2018.
16. J. C. Heigel, T. Q. Phan, J. C. Fox, and T. H. Gnaupel-Herold, "Experimental investigation of residual stress and its impact on machining in hybrid additive/subtractive manufacturing," Procedia Manuf., vol. 26, pp. 929-940, 2018.
17. W. Grzesik, "Hybrid additive and subtractive manufacturing processes and systems: A review," J. Mach. Eng., vol. 18, no. 4, pp. 5-24, 2018.
18. N. Khanna and J. Wadhwa, "Sustainable subtractive manufacturing: A systematic review," J. Manuf. Processes, vol. 58, pp. 574-591, 2020.
19. S. Smith, T. Schmitz, T. Feldhausen, and M. Sealy, "Hybrid metal additive/subtractive machine tools and applications," CIRP Ann., vol. 73, pp. 615-638, 2024.
20. H. Jayawardane, I. J. Davies, J. R. Gamage, M. John, and W. K. Biswas, "Sustainability perspectives - A review of additive and subtractive manufacturing," Sustain. Manuf. Service Econ., vol. 2, Art. no. 100015, 2023.
21. G. Manogharan, R. A. Wysk, and O. L. A. Harrysson, "Additive manufacturing-integrated hybrid manufacturing and subtractive processes: Economic model and analysis," Int. J. Comput. Integr. Manuf., vol. 29, no. 5, pp. 473-488, 2016.
22. Z. Zhu, V. G. Dhokia, A. Nassehi, and S. T. Newman, "A review of hybrid manufacturing processes - State of the art and future perspectives," Int. J. Comput. Integr. Manuf., vol. 26, no. 7, pp. 596-615, 2013.
23. J. M. Flynn, A. Shokrani, S. T. Newman, and V. Dhokia, "Hybrid additive and subtractive machine tools - Research and industrial developments," Int. J. Mach. Tools Manuf., vol. 101, pp. 79-101, 2016.
24. M. A. Rabalo, E. M. Rubio, B. Agustina, and A. M. Camacho, "Hybrid additive and subtractive manufacturing: Evolution of the concept and last trends in research and industry," Procedia CIRP, vol. 118, pp. 741-746, 2023.
25. M. L. Dezaki et al., "A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process," Adv. Powder Mater., vol. 1, no. 4, Art. no. 100054, 2022.
26. B. Freitas, V. Richhariya, M. Silva, A. Vaz, S. F. Lopes, and Ó. Carvalho, "A review of hybrid manufacturing: Integrating subtractive and additive manufacturing," Materials, vol. 18, no. 18, Art. no. 4249, 2025.
27. J. P. M. Pragana, R. F. V. Sampaio, I. M. F. Bragança, C. M. A. Silva, and P. A. F. Martins, "Hybrid metal additive manufacturing: A state-of-the-art review," Adv. Ind. Manuf. Eng., vol. 2, Art. no. 100032, 2021.
28. G. Campatelli, A. Scippa, F. Montevecchi, and N. Sallese, "Integrated WAAM-subtractive versus pure subtractive manufacturing approaches: An energy efficiency comparison," Int. J. Precis. Eng. Manuf.-Green Technol., vol. 7, pp. 1-11, 2020.
29. A. Al Rashid and M. Koç, "Additive manufacturing for sustainability and circular economy: Needs, challenges, and opportunities for 3D printing of recycled polymeric waste," Mater. Today Sustain., vol. 24, Art. no. 100529, 2023.

30. J. Su, W. L. Ng, J. An, W. Y. Yeong, C. K. Chua, and S. L. Sing, “Achieving sustainability by additive manufacturing: A state-of-the-art review and perspectives,” Virtual Phys. Prototyp., 2025.
31. O. Diegel, A. Nordin, and D. Motte, A Practical Guide to Design for Additive Manufacturing. Singapore: Springer, 2019.
32. J. Jiang and Y. Ma, “Path planning strategies to optimize accuracy, quality, build time and material use in additive manufacturing: A review,” Micromachines, vol. 11, no. 7, Art. no. 633, 2020.
33. T. Feldhausen et al., “Mechanical properties and microstructure of 316L stainless steel produced by hybrid manufacturing,” J. Mater. Process. Technol., vol. 290, Art. no. 116970, 2021.
34. H. Bui, H. A. Pierson, S. G. Nurre, and K. M. Sullivan, “Tool path planning optimization for multi-tool additive manufacturing,” Procedia Manuf., vol. 39, pp. 457-464, 2019.
35. P. C. Priarone, G. Ingarao, R. di Lorenzo, and L. Settineri, “A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining,” CIRP Ann., vol. 68, no. 1, pp. 37-40, 2019.
36. T. Peng, K. Kellens, R. Tang, C. Chen, and G. Chen, “Sustainability of additive manufacturing: An overview on its energy demand and environmental impact,” Addit. Manuf., vol. 21, pp. 694-704, 2018.
37. A. C. M. Bekker and J. C. Verlinden, “Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel,” J. Clean. Prod., vol. 177, pp. 438-447, 2018.
38. A. Wippermann, T. G. Gutowski, B. Denkena, M. A. Dittrich, and Y. Wessarges, “Electrical energy and material efficiency analysis of machining, additive and hybrid manufacturing,” J. Clean. Prod., vol. 251, Art. no. 119731, 2020.
39. U. M. Dilberoglu, B. Gharehpapagh, U. Yaman, and M. Dolen, “Current trends and research opportunities in hybrid additive manufacturing,” Int. J. Adv. Manuf. Technol., vol. 113, pp. 623-648, 2021.
40. J. P. G. Magrinho, “Innovation trends in hybrid additive manufacturing: A bibliometric and technology life cycle analysis,” Int. J. Adv. Manuf. Technol., vol. 143, pp. 7273-7291, 2026.
41. ASTM International, ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies. West Conshohocken, PA, USA: ASTM Int., 2015.
42. M. Mazur, M. Leary, M. McMillan, J. Elambasseril, and M. Brandt, “SLM additive manufacture of H13 tool steel with conformal cooling and structural lattices,” Rapid Prototyp. J., vol. 22, no. 3, pp. 504-518, 2016.
43. H. Paris, H. Mokhtarian, E. Coatanéa, M. Museau, and I. F. Ituarte, “Comparative environmental impacts of additive and subtractive manufacturing technologies,” CIRP Ann., vol. 65, no. 1, pp. 29-32, 2016.
44. F. Walachowicz et al., “Comparative energy, resource and recycling life cycle analysis of gas turbine burner repair technologies,” J. Ind. Ecol., vol. 21, no. S1, pp. S203-S215, 2017.
45. D. Strong, I. Kay, B. Conner, T. Wakefield, and G. Manogharan, “Hybrid manufacturing - Integrating traditional manufacturers with additive manufacturing supply chain,” Addit. Manuf., vol. 21, pp. 159-173, 2018.
46. B. Lauwers et al., “Hybrid processes in manufacturing,” CIRP Ann., vol. 63, no. 2, pp. 561-583, 2014.
47. X. Zhang, W. Li, X. Chen, W. Cui, and F. Liou, “Evaluation of component repair using direct metal deposition from scanned data,” Int. J. Adv. Manuf. Technol., vol. 95, pp. 3335-3348, 2018.
48. M. Jackson, A. Kestler, J. Smith, and T. Gutowski, “A comparison of energy consumption in wire-based and powder-based additive-subtractive manufacturing,” Procedia Manuf., vol. 5, pp. 989-1005, 2016.
49. L. Chong, S. Ramakrishna, and S. Singh, “A review of digital manufacturing-based hybrid additive manufacturing processes,” Int. J. Adv. Manuf. Technol., vol. 95, pp. 2281-2300, 2018.
50. S. Graziosi, J. Faludi, T. Stanković, et al., “A vision for sustainable additive manufacturing,” Nature Sustain., vol. 7, no. 6, pp. 698-705, 2024.
51. G. Taddese, S. Durieux, and E. Duc, “Sustainability performance indicators for additive manufacturing: A literature review based on product life cycle studies,” Int. J. Adv. Manuf. Technol., vol. 107, pp. 3109-3134, 2020.