

From Powder to Performance: Integrated Manufacturing and Post-Processing Strategies for Titanium Alloys

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How To Cite: Pedroso, A.F.V.; Pinto, A.G.; Azevedo, A.; et al. From Powder to Performance: Integrated Manufacturing and Post-Processing Strategies for Titanium Alloys. *Journal of Mechanical Engineering and Manufacturing* **2026**. <https://doi.org/10.53941/jmem.2026.100034>

Received: 5 April 2026

Revised: 11 June 2026

Accepted: 30 June 2026

Published: 28 September 2026

Abstract: Titanium (Ti) alloys are critical engineering materials widely used in aerospace, biomedical, and high-performance applications due to their high strength-to-weight ratio, corrosion resistance, and biocompatibility. However, their broader adoption remains constrained by complex processing routes, high production costs, and significant challenges in machining and finishing. This review adopts a process chain perspective, analysing how manufacturing routes and post-processing strategies collectively determine the final performance of Ti-alloy components. It provides an integrated assessment of titanium alloy manufacturing routes, including casting, powder metallurgy, additive manufacturing, and hybrid additive–subtractive techniques, and evaluates their influence on microstructure, defect formation, dimensional accuracy, surface integrity, and mechanical behaviour. Emphasis is placed on post-processing operations, such as heat treatment, hot isostatic pressing, machining, and surface finishing, as essential stages for achieving the required structural integrity and service performance. The review further highlights the trade-offs associated with key additive manufacturing technologies, including powder bed fusion, directed energy deposition, and wire arc additive manufacturing, particularly in terms of strength, ductility, geometric capability, and surface quality. Hybrid manufacturing approaches are identified as especially promising because they integrate additive deposition with precision machining, enabling improved dimensional control and surface integrity. Finally, future directions are outlined in relation to process integration, digital manufacturing, predictive modelling, and improved process monitoring. Overall, the review demonstrates that the performance and reliability of Ti-alloy components should be understood as the result of an integrated manufacturing and post-processing process chain, rather than as the outcome of any single manufacturing process considered in isolation.

Keywords: titanium alloys; additive manufacturing; hybrid manufacturing; post-processing; heat treatment; surface finishing

1. Introduction

Titanium (Ti), a transition metal with a distinctive silver colour, was first discovered in 1791 by William Gregor. Interestingly, the metal was named after the titans, reflecting its strong affinity for other elements, particularly Oxygen



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(O) and Nitrogen (N), which accounts for the difficulty in its extraction. It has since emerged as a vital material in various industries, thanks to its unique combination of strength, lightness, and corrosion resistance [1].

Ti-alloys are essential materials in various industries due to their unique properties. The process of obtaining these alloys involves several key steps, from extracting Ti ore to producing the final alloy. The first step in obtaining Ti-alloys is the extraction of Ti ore, primarily from ilmenite (FeTiO_3) and rutile (TiO_2) minerals. The Ti-ore deposits are predominantly found in igneous and metamorphic rocks and in sedimentary deposits and are distributed in over 20 countries [2]. Once extracted, the ore is purified to produce Ti dioxide, which is then converted into Ti-tetrachloride (TiCl_4) through a process called the chloride process. This involves reacting the Ti-dioxide (TiO_2 , or also called Ti-oxide IV) with chlorine (Cl) and coke at high temperatures [3–5].

Ti-metal is produced from TiCl_4 using either the Kroll or Hunter process. The Kroll process is more widely used and involves reducing TiCl_4 with Magnesium (Mg) in a large and sealed reactor. This process yields Ti sponge, which is then melted and formed into ingots [6,7].

To produce Ti-alloys, the pure Ti is alloyed with other elements such as Aluminium (Al), Vanadium (V), Molybdenum (Mo) and Iron (Fe). This is typically done in a vacuum arc remelting furnace, where precise control of temperature and atmosphere is possible [8]. The addition of these alloying elements enhances the mechanical and physical properties of the final alloy [9]. The final step involves processing the Ti-alloys into desired forms, such as sheets, bars, or tubes. This may include hot and cold working processes, heat treatment, and machining to achieve the required specifications for various applications [10].

Ti-alloys are widely used in high-performance engineering because they combine low density, high strength-to-weight ratio, corrosion resistance, fracture toughness, high-temperature capability, and biocompatibility [11–18]. These characteristics explain their extensive use in aerospace structures, biomedical implants, automotive components, marine systems, chemical processing, and other demanding applications where weight reduction, durability, and reliability are critical [19–21]. Nevertheless, their wider adoption remains limited by high extraction and processing costs, difficult machinability, rapid Tool Wear (TW), fatigue sensitivity, and the need for carefully controlled manufacturing and post-processing routes [20–23]. These advantages and limitations provide the technical basis for the present review, which focuses on how integrated manufacturing and post-processing strategies can improve the performance and industrial viability of Ti-alloy components. Ti-alloys can be subdivided into near- α and metastable β alloys [24,25]. Figure 1 displays the family of α and β -Ti-alloys found.

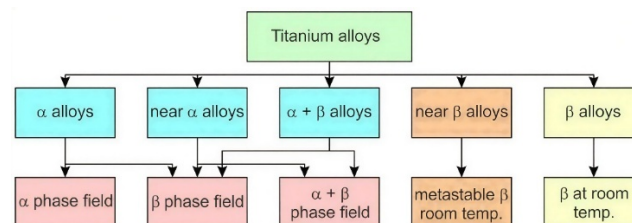


Figure 1. Classification of Ti-alloys based on phase constitution, including α , near- α , $\alpha + \beta$, near- β , and β alloy systems [26].

Alpha (α) Ti-alloys are composed primarily of the α phase [27]. These alloys have good strength and excellent corrosion resistance, even at high temperatures. However, they are generally less strong than β [28] or α - β [29] alloys. α alloys are often used in environments where corrosion resistance is crucial, such as in chemical processing and marine applications. An example of an α alloy is commercially pure Ti (ASTM grade 1, 2, 3 and 4 Ti/Pd alloys, ASTM grade 7 and 11).

β alloys, on the other hand, are mainly composed of the beta phase, characterized by a body-centered cubic (BCC) crystal structure. These alloys are heat treatable, which allows for a significant increase in strength. β alloys have higher strength than α alloys and are more ductile. They can be processed easily and are used in applications requiring high strength-to-weight ratios, such as aerospace structural components. Ti15V3Cr3Sn3Al is an example of a β alloy [23].

α - β alloys contain a mix of both α and β phases and combine some of the best properties of both alloy types. They can be heat treated, offering a balance of formability, strength, and ductility. These alloys are versatile and widely used, particularly in aerospace applications, due to their good mechanical properties at a wide range of temperatures. Ti6Al4V is the most widely used Ti-alloy, falling into this category [13]. The Ti6Al4V alloy, was developed in the 1940, and stands out as one of the most popular and widely used Ti-alloys. It demonstrates the low-density characteristic of Ti—60% less than that of steel and superalloys—which, when combined with alloying and deformation processing, results in significantly improved strength [13].

Ti6Al4V, also known as Grade 5 Ti, is the most widely used $\alpha + \beta$ Ti-alloy due to its favourable combination of low density, high strength-to-weight ratio, corrosion resistance, elevated-temperature capability, and biocompatibility [30–34]. These properties make it particularly relevant for aerospace structures, biomedical implants, and high-performance automotive components, where reliability, weight reduction, and long-term service performance are essential [31–36]. However, despite these advantages, Ti6Al4V remains challenging to process and machine, reinforcing the need for appropriate manufacturing route selection and effective post-processing strategies.

Several mechanical processes are employed in the production of Ti-alloys, and these processes vary depending on the desired final product and application. Here are listed some common mechanical processes used with Ti-alloys and the resulting products [36].

- **Machining:** involves removing material from a workpiece to achieve the desired shape and dimensions. Common machining techniques for Ti-alloys include turning, milling, and drilling. Used to obtain components with intricate shapes, such as aerospace parts and medical implants [37]
- **Forging:** involves deforming metal by applying compressive force using a hammer or a press. It improves the mechanical properties and grain structure of Ti-alloys. Mainly used for production of aircraft components, automotive parts, and structural components [38].
- **Extrusion:** is the process of shaping material by forcing it through a die. It is commonly used to produce long and uniform profiles, such as tubes, rods, and other long sections used in various applications [39].
- **Rolling:** involves reducing the thickness of a metal sheet or plate by passing it through a pair of rollers. It improves the mechanical properties and surface finish of Ti-alloys. Sheets, plates, and foils for applications in aerospace and industrial sectors are commonly produced by this process [40].
- **Investment casting or precision casting** is a process where a wax pattern is coated with a ceramic shell, melted, and replaced with molten metal. It allows for complex and near-net-shape components. Used for obtaining complex and intricate components for aerospace, medical, and industrial applications [41].
- **Additive Manufacturing (AM):** this process deposits Ti material layer by layer from a three-dimensional digital model, enabling the production of complex geometries that would be difficult or impossible to obtain by conventional manufacturing routes. Adding material layer by layer makes it possible to create complex parts and intricate geometries that would be difficult or impossible to produce using traditional methods [42].

The industrialisation of AM has advanced significantly in recent years, with rapid growth in applications ranging from dental components and medical implants to aerospace structures. This evolution commenced with the production of dental items and medical implants, subsequently extending its reach to the aerospace sector [43]

AM offers a myriad of advantages, including reduced waste, expanded design possibilities, enhanced product functionality, and increased production flexibility. Noteworthy instances include the fabrication of intricate components that are either costly or unfeasible to produce through traditional methods. Additionally, AM facilitates the creation of single components by consolidating numerous separate pieces, a feat difficult to achieve using other manufacturing techniques.

Another notable application involves the development of tools featuring curved cooling channels for optimized cooling. Furthermore, AM enables the production of lightweight parts with topology optimization, leading to substantial reductions in weight, as well as significant decreases in lead times, costs, and waste compared to conventional manufacturing methods [44,45].

Exemplary cases from various corners of the globe underscore the remarkable achievements in weight reduction, along with the considerable benefits of diminished lead times, costs, and waste when contrasted with traditional manufacturing processes. This underscores the transformative impact and potential of AM in diverse industries [46].

The aerospace industry has indeed witnessed significant advancements in metal 3D printing, and two notable techniques, Selective Laser Melting (SLM) and Electron Beam Melting (EBM), have stood out prominently [47]. These techniques have proven highly effective, particularly in the aerospace sector, where the demand for manufacturing complex parts with low production volumes and minimal weight is crucial [48].

The choice of raw materials in metal 3D printing for aerospace applications commonly includes Ti, Al-alloys, and specific types of steel. These materials offer a combination of strength, lightweight properties, and corrosion resistance, which are crucial factors in the aerospace industry [49].

It's interesting to also note that, according to the information provided, approximately 14% of Metal Additive (MA) parts produced for the automotive industry in series production find application in vehicle engines. This highlights the growing integration of metal 3D printing technologies in the automotive sector, where the unique capabilities of these techniques are leveraged for manufacturing engine components with enhanced performance characteristics [50]. On the Table 1 are indicated the seven types of additive manufacturing process that can be used for metal.

Table 1. Raw materials used in the AM processes.

AM Technology	Material Used
Binder Jetting (BJ)	CoCr, Steel, Tungsten (W), Tungsten Carbide (WC)
Direct Energy Deposition (DED)	Al, Cobalt (Co), Nickel (Ni), Steel, Ti
Direct Metal Laser Sintering (DMLS)	Al, CoCr, Ni, Steel, Ti
EBM	Al, CoCr, Ni, Steel, Ti
SLM	Al, CoCr, Ni, Steel, Ti
Ultrasonic Additive Manufacturing (UAM)	Al, Copper (Cu)

Table 1 shows that Ti and Ti-alloys are compatible with several AM routes, particularly DED, DMLS, EBM, and SLM, confirming the broad relevance of AM for Ti-based manufacturing.

The four most commonly used AM techniques are: Powder Bed Fusion (PBF), DED, BJ [51] and Sheet Lamination (SL) [52,53]. When using SLM, the absorption of the laser beam differs for each type of metal, leads to surface tensions and increasing thermal stress, which can cause cracks being this a disadvantage of this technique. The DMLS method is a technique that allows the use of different types of metals, it is expensive compared to other techniques and its use is restricted to a few applications, such as the manufacture of prototypes in the aerospace industry [48]. There are several studies focus on new emerging techniques for AM, like Wire Arc Additive Manufacturing (WAAM), and cold spraying additive manufacturing (CSAM), demonstrating that parts produced by WAAM exhibits lower accuracy due to factors such as wire deposition and heat transfer. Conversely, surfaces produced by WAAM tend to be rougher due to larger deposition sizes [38]. Table 2 compares some of the main characteristics of parts obtained by different AM techniques while Tables 3–5 focus on the mechanical properties of AMed Ti-6Al-4V products.

Table 2. Comparative qualitative characteristics of Ti-alloy components produced by SLM, EBM, and WAAM processes [38,54].

	SLM	EBM	WAAM
Density	CH	H	H
Print	S	S	Lg
Size	H	CH	L
Accuracy	H	M	CH
Surface Quality	H	L	H
Residual Stress	CL	H	L
Equipment Cost			

Caption: Comparatively high (CH); High (H); Moderate (M); Small (S); Low (L); Large (Lg); Comparatively Low (CL).

Table 2 shows that SLM and EBM generally provide better accuracy and surface quality, whereas WAAM prioritises larger build size and lower equipment cost at the expense of dimensional precision.

Table 3. Mechanical properties of Ti-6Al-4V components produced by the SLM process [38,54–58].

Material	σ_u (MPa)	σ_y (MPa)	ϵ_u (%)
Ti-6Al-4V	1211 ± 31	1100 ± 12	6.5 ± 0.6
	1267 ± 5	1110 ± 9	7.3 ± 1.1
	1149 ± 11	1093 ± 15	11.3 ± 0.5
	1090 ± 10	1022 ± 10	12.7 ± 2.1
	1165 ± 2	1112 ± 3	11.6 ± 1.2
	1095 ± 10	990 ± 5	8.1 ± 0.3
	1421 ± 120	1273 ± 53	3.2 ± 0.5
	1166 ± 25	962 ± 47	1.7 ± 0.3
	1206 ± 8	1137 ± 20	7.6 ± 2
	1219 ± 20	1143 ± 30	4.89 ± 0.6
	1269 ± 9	1195 ± 19	5 ± 0.5
	1250	1125	6

Caption: ϵ_u —strain at fracture, σ_u —ultimate strength, σ_y —yield strength.

Table 3 shows that SLM Ti-6Al-4V components commonly achieve high tensile and yield strength, although ductility varies considerably depending on processing and post-processing conditions.

Table 4. Mechanical properties of Ti-6Al-4V components produced by the EBM process [38,59–62].

Material	σ_u (MPa)	σ_y (MPa)	ϵ_u (%)
Ti-6Al-4V	950–990	910–940	14–16
	1150–1200	1100–1150	16–25
	994–1029	883–938	11.6–13.6
	930	865	12–17
	944.5–964.5	823.4–851.8	13.2–16.3
	≈990–1180	≈900–1100	≈18–23
	915	830	13.1
	1012 ± 3	962 ± 4	8.8 ± 1.6
	1011 ± 4	947 ± 11	9 ± 1.1
	790 ± 10	740 ± 10	2.2 ± 0.3
	833 ± 22	783 ± 15	2.7 ± 0.4
	851 ± 19	812 ± 12	3.6 ± 0.9

Table 4 indicates that EBM Ti-6Al-4V generally provides a more balanced strength–ductility response than SLM, although mechanical performance remains sensitive to process parameters and post-processing.

Table 5. Mechanical properties of Ti-6Al-4V components produced by the WAAM process [38,62–69].

Material	σ_u (MPa)	σ_y (MPa)	ϵ_u (%)
Ti-6Al-4V	929 ± 41	\	9 ± 1.2
	939 ± 24	\	16 ± 3
	918 ± 17	803 ± 15	14.8
	937 ± 21	861 ± 14	16.5 ± 2.7
	820 ± 6.23	710 ± 4	7.18 ± 0.93
	988 ± 19.2	909 ± 13.6	7 ± 0.5
	902–923	881–906	6.4
	1166.3 ± 22.1	1059.1 ± 18.4	5.97 ± 0.65
	929 ± 41	\	9 ± 1.2
	939 ± 24	\	16 ± 3
	918 ± 17	803 ± 15	14.8
	937 ± 21	861 ± 14	16.5 ± 2.7

Table 5 shows that WAAM Ti-6Al-4V can achieve competitive tensile properties, but its performance is strongly influenced by thermal history, anisotropy, and subsequent post-processing.

The Ti-6Al-4V alloy, has emerged as one of the pioneering alloys manufactured through the EBM process [70]. This advancement was primarily driven by the biomedical industry, which recognized the substantial potential of the Ti6Al4V alloy for creating personalized surgical implants. The ability to produce customized surgical implants tailored to the specific needs of individual patients has been a transformative aspect of using Ti6Al4V alloy in the EBM process. This not only enhances the overall performance and longevity of implants but also contributes to better patient outcomes [71].

The EBM process involves selectively melting metal powder layer by layer using an electron beam. This additive manufacturing technique allows for intricate and customized designs, making it particularly suitable for biomedical applications where patient-specific implants are often required [72].

Some studies demonstrate that using BJ and as the processes is carried out at room temperature, for the metal to have structural resistance, it is necessary to carry out a post-processing to remove the bonding agent and, at the same time, have a resistant metal part. For this post-processing that can be used two techniques: infiltration and sintering [73].

In the infiltration technique first the binding agent is removed, leaving a porous structure, by heating empty spaces are created within the porous structure and then filled with the molten metal, resulting in a bimetallic part. The sintering method the binding agent is “burned off” on a furnace leaving the metal powder particles, the remaining metal powder particles are then sintered or fused together at high temperatures, resulting in a solid, high-density part [48].

DED processes is most used to repair parts or add metal to manufactured parts. The technique is promising for use in components requiring structural strength, as it produces parts with high resistance and there are many materials that can be used. On the other hand, its disadvantages include poor geometric accuracy and difficult control of the weld puddle.

Recently, the researchers have demonstrated that AM processes can produce metal parts with mechanical performances different from the wrought ones. In particular, the hardness and wear resistance of the AM metals have revealed to be superior to conventional casting ones because the after appropriate post processing, AM components may exhibit improved surface wear performance [48].

Various methods are used for metal fabrication, each adapted to different needs, materials, and geometries. The most common types of metal fabrication methods can involve casting, forging, rolling, extrusion, CNC machining, welding powder metallurgy, additive manufacturing (AM) and others [74].

Each method has its advantages and limitations, and the choice depends on the desired characteristics of the part, the volume of production, the material used and other factors specific to the project.

The continual progress in AM technologies underscores the dedication of researchers and industry experts to overcoming challenges, paving the way to produce metal parts that closely emulate or even surpass the properties of traditionally manufactured components.

The dynamic and collaborative nature of additive manufacturing positions the industry to deliver metal parts that not only rival but often surpass the properties of traditionally manufactured components, marking a significant stride towards the future of advanced manufacturing.

AM parts are often compared to castings, conceptually, as a reasonable facsimile, since melting of powder with a laser, plasma or an electronic beam is comparable to what happens in a casting on a micro scale. But that can be also the same micro porosity problems; they have to be fed with liquid metal to avoid porosities. Another problem refers to when liquid metal turns to solid and it shrinks and dimensions needs to be adjusted. The shrink is not equal in all 3 dimensions since parts are not allowed to shrink freely in space but are obstructed by geometry. So rules have to be made for each part to compensate for shrinkage. Nowadays, the AM processes use scale factors which are used to scale the part to compensate for this shrinkage in each dimension [75].

In Table 6 are compared the Surface Roughness (SR) from different processes of metal parts production. The SR is also a challenge on demand for the AM technology compared with some of the most commonly used traditional processes [44,45].

Table 6. SR after various manufacturing processes [76].

Process	IT Classes											
	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16
Casting												
Sintering												
Drop forging												
Precision forging												
Extrusion												
Rolling												
Cutting												
Jigging												
Drilling												
Milling												
Planing												
Broaching												
Grinding												
AM												

Table 6 highlights that AM processes generally face greater dimensional-accuracy and surface-quality limitations than precision subtractive or finishing processes, reinforcing the need for post-processing.

Standard ISO 286-1:2010(E) [76] is part of a series of international standards that establish tolerances for linear dimensions of mechanical parts. It provides a table of dimensional tolerances for shafts and bores in metric systems. Tolerances are specified in terms of tolerance classes numbered IT-01 to IT-18. The lower the number, the tighter the tolerances. Is easy to understand that AM processes has is limitation when the goal is dimension accuracy. Even using an additive manufacturing technique is commonly needed a post-processing processes to conform and give the parts the desired shape, dimensions and mechanical properties. In the Ti-alloys it can be a very difficult task [77].

The post-processing of Ti-alloys, after AM or even casting, can pose specific challenges due to the unique properties of Ti and the extreme processing conditions [41]. Some common problems in the post-processing of Ti-alloys can include:

- Machining difficulties due to the low thermal conductivity and high chemical reactivity of the Ti alloy, that can lead to rapid TW and demand of specific machining techniques [78,79]

- During machining, Ti can form sharp edges, which can compromise the quality of the machined part and increase the risk of injuries to operators [80].
- atmospheres containing oxygen leads to oxidation and the formation of undesirable surface layers, compromising part integrity [81]
- heat treatment of Ti parts may be necessary to enhance their mechanical properties [82]
- plastic deformation at low temperatures can be employed to improve the mechanical properties but may lead to increased brittleness and the need for subsequent heat treatments.
- In additive manufacturing processes, thermal processing anomalies may occur, leading to variations in properties that require careful consideration in design and post-processing.
- Due to the anisotropy, mechanical properties may vary in different directions, necessitating careful considerations in design and post-processing [73]
- Post-processing of Ti-alloys can be costly due to specialized techniques, high-quality machining tools, and additional quality control measures.

To address these challenges, it is crucial to employ specific techniques and processes tailored to Ti and to use appropriate tools and equipment.

Collaboration between materials engineers, manufacturers, and processing experts is essential to optimize the post-processing of Ti-alloys and ensure the quality of the final parts.

The machining of Ti6Al4V is however possible, even without lubrication [83]. Ti-alloys are easily damaged during machining. The damage appears as micro cracks, build up edge, plastic deformation, heat affected zones and tension residual stresses manufacturing [30].

Post-process methods such as heat-treatment (HT), machining (M), hot isostatic pressing (HIP), and different combinations thereof have been explored to enhance the mechanical as well as the fatigue properties [84]

The manufacture of mechanically robust and cost-effective metallic components with complex geometries remains a central challenge in aerospace, biomedical, automotive, tooling, and consumer product folks (Figure 2). To speed things up, simplify the whole manufacturing deal, and slash costs for these industry goodies, researchers are digging into combining lots of manufacturing steps into just one machine. The end goal is to reduce production space, time, and manpower requirements. Integrated systems are increasingly being recognized to meet these goals [85].

Hybrid processes were developed to reply to this issue, based on a principle of addition of material followed by the removing of material on the same machine. The deposition process allows reaching a “near net shape” and the process of machining a “final form” [30].

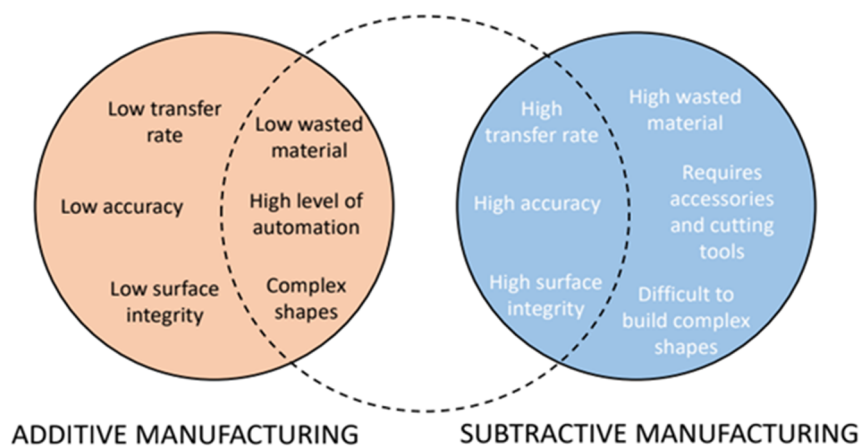


Figure 2. Flowchart comparative AM and traditional processes.

Hybrid processes become economically competitive when deposited materials are rare, expensive, and difficult to machine, like Ti-alloys, ranked among the most difficult to machine materials [30]. Hybrid manufacturing leverages the advantages of both AM and machining to create parts that have complex geometries, and a demand for tight tolerances and excellent surface finish. The residual stresses created by the two processes is a challenge [86]. AM generates very high residual stresses due to the thermal history imposed by the process. These stresses can cause the part to crack and separate from the build plate or to distort significantly, causing the part to fail or not meet the design requirements. Also, In the post-processing of additively manufactured parts, the propagation of geometric errors can impact the machined surface accuracy of the final product [86].

The high stresses may induce distortion that can damage the part during the AM process, and it leads to unexpected problems during machining. Some studies were found on works about the residual's stresses caused by Laser Powder Bed Fusion process on stainless steel cylinders. The distortion was calculated and estimated by measuring the outer diameter before and after the machining process. This allowed to anticipate the distortion before the machining process and adjust the parameters programmed on the machine [86]. Hybrid additive/subtractive manufacturing is a process that combines both AM and subtractive manufacturing, to create parts with high complexity, tight tolerances, and good surface finish [87]. This processing can be done in the same equipment, where both AM and machining operations are performed [88]. The AM processing enables complex geometries to be created while the machining creates better geometric accuracy and surface finish [86]. While AM processes inherently create parts with high residual stresses that, hybrid manufacturing removes portions of the stressed material [86].

Hybrid manufacturing involves the integration of different manufacturing processes to create products or components. In the context of Ti-alloy processing, the hybrid approach can be employed to leverage the unique characteristics of this material and overcome specific challenges. It plays a crucial role in tool molds and reconstruct of pieces with damage areas. For example, die casting molds can be provided with a core made of a bronze alloy and provided with a layer of hot-work tool steel. Or repair of tool molds where material is first applied to a damaged and with a subsequent milling process a finish machining is carried out to restore the original quality of the piece [89].

The advanced manufacturing technique enables the optimization of production by capitalizing on the advantages of diverse processes. However, it is crucial to consider the specific challenges associated with Ti, such as machining difficulty and chemical reactivity, when developing hybrid approaches. The effective integration of processes can result in Ti components with improved properties and enhanced production efficiency [41].

Some hybrid manufacturing approaches for Ti-alloys may include:

- AM with post-processing machining to achieve tight tolerances, remove imperfect surface layers, or refine fine details [90].
- Integrated welding to join Ti components and machining operations to ensure dimensional accuracy and surface integrity [91].
- Combined hot and cold working to optimize the mechanical properties of Ti. This may include hot forming followed by cold working operations to enhance strength and toughness [92].
- Customized heat treatment such as quenching, tempering, and other treatments to adjust the mechanical characteristics of Ti [93].
- Combination of different AM processes to involve the use of multiple materials or deposition methods to create more complex components.

There have been surging some companies dedicated to the concept of hybrid machines, such as DMG MORI, RENISHAW, EOS, GE ADDITIVE, SLM SOLUTIONS. This market is growing fast following the industrial market demand.

But necessary there are also some disadvantages when using a hybrid manufacturing. Some are listed above:

- Residual stresses from additive step can be reviled on the subtractive step [94].
- Recycling of the powder, liquids and, oils and cutting fluids.
- Protection of the machine (cooling system).
- Training of qualified technicians.
- Costs of the equipment.
- Costs of the powder metal.
- High setup time.
- Possibility of interference of the cutting or milling fluids.

In this context, the increasing availability of digital manufacturing technologies, advanced sensing platforms, data-driven analytics, and computationally assisted process control offers a promising means of addressing many of the limitations currently associated with the manufacture of Ti-alloys. The integration of real-time monitoring, process simulation, sensor-informed feedback, and predictive modelling creates the possibility of more intelligent manufacturing environments capable of improving process consistency across additive, hybrid, and post-processing routes. Such developments may contribute to enhanced dimensional accuracy, improved surface integrity, more effective residual-stress management, reduced defect occurrence, and, ultimately, the more reliable industrial adoption of Ti-alloy components for demanding engineering applications.

Against this background, the present study examines the evolving technological landscape surrounding the production, processing, and post-treatment of Ti-alloys, with particular emphasis on AM, hybrid manufacturing,

and the challenges associated with subsequent finishing and performance enhancement. The objective is to provide a systematic and critically informed overview of the ways in which advanced manufacturing strategies, digitally assisted process optimisation, and emerging monitoring methodologies may support improved reliability, manufacturing efficiency, and broader industrial implementation of Ti-based components.

Accordingly, the central premise of this review is that Ti-alloy manufacturing should be understood as an integrated process chain, rather than as a sequence of isolated operations. From feedstock selection and primary manufacturing route to heat treatment, hot isostatic pressing, machining, surface finishing, and final inspection, each stage influences the microstructure, defect population, dimensional accuracy, surface integrity, and mechanical performance of the final component. This process-chain perspective is particularly important for AM and hybrid manufacturing, where near-net-shape fabrication can reduce material waste and expand design freedom, but where post-processing remains essential for converting the as-built or as-deposited state into a component suitable for demanding service conditions. The novelty of this review lies in the integration of additive, hybrid, and post-processing stages within a unified process–performance framework supported by a systematic PRISMA-based methodology. Figure 3 provides a visual synthesis of the process-chain perspective adopted in this review, illustrating how additive and hybrid manufacturing routes generate characteristic defects and material conditions that must subsequently be addressed through post-processing in order to achieve the required final performance of Ti-alloy components.

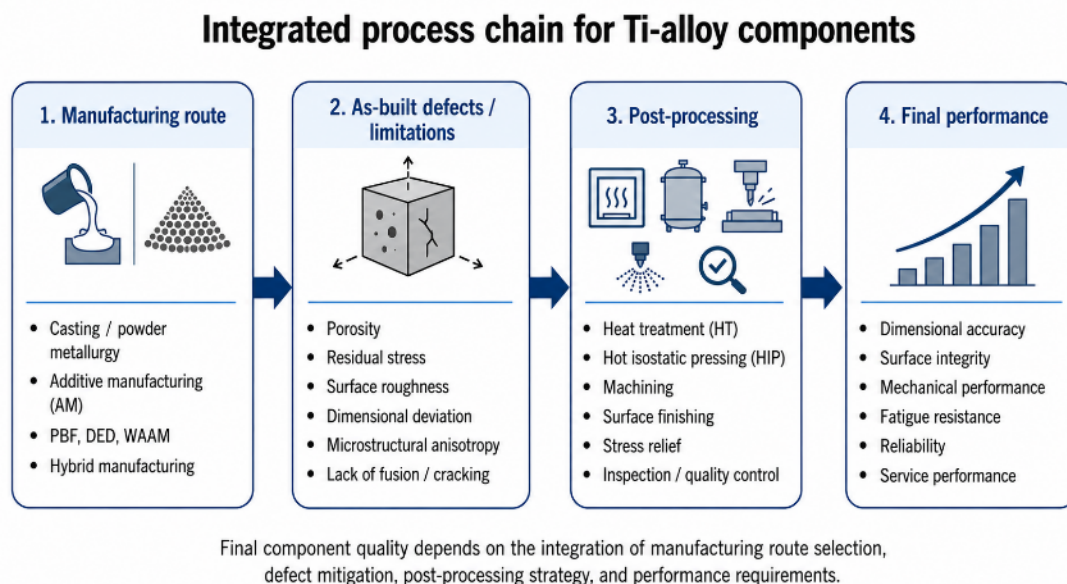


Figure 3. Schematic representation of the integrated process chain for Ti-alloy components, showing the relationship between additive and hybrid manufacturing routes, process-induced defects, post-processing operations, and final performance outcomes.

The manuscript is organised into ten principal sections and one appendix. Section 1 introduces the scientific and industrial context of Ti and its alloys, outlining their property profile, application relevance, processing limitations, and the process-chain rationale that frames the review. Section 2 presents the PRISMA-based research methodology, including the information sources consulted, Boolean search strategy, eligibility criteria, study-selection procedure, PICOC formulation, and Quality Assessment framework adopted to ensure transparency, reproducibility, and methodological rigour. Section 3 develops the literature review, examining the principal manufacturing routes for Ti-alloys, with emphasis on additive manufacturing, hybrid additive–subtractive strategies, process-induced defects, machining behaviour, and post-processing requirements. Section 4 introduces the Integrated Ti-Alloy Manufacturing Quality Framework, linking process parameters, microstructural evolution, defect formation, surface integrity, and functional performance within a unified process–performance framework. Section 5 examines surface integrity as a critical link between manufacturing route and service behaviour, particularly in relation to fatigue, wear, corrosion resistance, and structural reliability. Section 6 presents a defect taxonomy and discusses the principal failure mechanisms associated with Ti-alloy manufacturing. Section 7 analyses hybrid manufacturing as a transition from near-net-shape fabrication to functional reliability, with particular attention to the integration of additive deposition, machining, heat treatment, and finishing operations. Section 8 provides the critical discussion, synthesising publication trends, process-family trade-offs, post-

processing requirements, defect mitigation strategies, and the implications of current advances for Ti-alloy manufacture. Section 9 outlines a future research roadmap for advanced Ti-alloy manufacturing systems, focusing on process integration, digital manufacturing, predictive modelling, in-situ monitoring, hybrid process planning, and standardised qualification routes. Section 10 presents the main conclusions, emphasising that the performance and reliability of Ti-alloy components must be understood as the outcome of an integrated manufacturing and post-processing process chain, rather than of any single process considered in isolation. Appendix A provides supplementary methodological material, namely the PRISMA 2020 flow diagram, which documents the identification, screening, eligibility assessment, and inclusion of studies considered in the review.

2. Method of Research

A structured and comprehensive literature review was undertaken using a transparent and reproducible methodological approach. The review process was developed in accordance with the PRISMA 2020 guidelines [95,96] thereby ensuring procedural consistency, methodological transparency, and replicability throughout the study. The identification, screening, and critical appraisal of relevant sources were informed by recognised indicators of scholarly quality, including citation relevance, technical contribution, and the academic standing of the publication venues [97].

Data collection was carried out in January 2026, with the initial body of bibliographic records being retrieved principally from the CrossRef database, selected on account of its broad indexing coverage across the fields of engineering, materials science, and advanced manufacturing. In order to widen the scope of retrieval and improve the completeness and reliability of bibliographic metadata, additional indexing platforms, most notably Dimensions.ai, were also consulted.

To support the systematic consolidation of records obtained from multiple databases, a customised MATLAB® routine was developed. This tool enabled the automated integration of search results [98], the harmonisation of bibliographic metadata, and the identification and elimination of duplicate records. The adoption of this semi-automated workflow enhanced both the efficiency and the robustness of the literature selection procedure, particularly for a multidisciplinary field spanning Ti-alloy metallurgy, additive and hybrid manufacturing, and associated post-processing strategies.

2.1. Search Strategy and Information Sources

Building upon the PRISMA-based methodological framework outlined above, the literature search strategy was specifically developed to identify studies addressing the manufacture and post-processing of Ti-alloys, with particular emphasis on additive and hybrid manufacturing routes, rather than general contributions on metallic processing or conventional machining considered in isolation. The search protocol was structured to ensure thematic precision and to maximise the relevance of the retrieved literature through the use of three complementary conceptual groups of keywords.

The first group concerned Ti-alloy materials and alloy systems, including terms such as “*titanium alloys*”, “*Ti-alloys*”, “*α titanium alloys*”, “*α + β titanium alloys*”, “*β titanium alloys*” and “*γ titanium alloys*”. The second group addressed advanced manufacturing routes, incorporating terms such as “*additive manufacturing*”, “*metal additive manufacturing*”, “*laser powder bed fusion*”, “*selective laser melting*”, “*electron beam melting*”, “*directed energy deposition*”, “*wire arc additive manufacturing*”, “*hybrid manufacturing*”, and “*hybrid additive-subtractive manufacturing*”. The third group focused on post-processing and performance-related aspects, including “*post-processing*”, “*post-treatment*”, “*heat treatment*”, “*surface finishing*”, “*machining*”, “*hot isostatic pressing*”, “*residual stress*”, “*surface roughness*”, “*dimensional accuracy*”, “*microstructure*”, and “*fatigue performance*”.

The Boolean search logic followed the general structure:

(“Titanium Alloys” OR “Ti-Alloys” OR “α titanium alloys” OR “β titanium alloys” OR “γ titanium alloys” OR “α + β Titanium”)

AND (“Additive Manufacturing” OR “Laser Powder Bed Fusion” OR “Selective Laser Melting” OR “Electron Beam Melting” OR “Directed Energy Deposition” OR “Wire Arc Additive Manufacturing” OR “Hybrid Manufacturing” OR “Hybrid Additive-Subtractive Manufacturing”)

AND (“Post-processing” OR “Post-treatment” OR “Heat Treatment” OR “Surface Finishing” OR “Machining” OR “Hot Isostatic Pressing” OR “Residual Stress” OR “Surface Roughness”)

Search queries were applied to the title, abstract, and keyword fields of the selected databases. In order to ensure the scientific relevance, comparability, and technical consistency of the collected literature, the following eligibility criteria were adopted:

- Publication period: 2010–2025
- Document type: peer-reviewed journal articles and review papers
- Language: English

These criteria were introduced to ensure that the review captured the most relevant contemporary developments in the processing of Ti-alloys, particularly in relation to AM, hybrid manufacturing strategies, and post-processing methodologies, while excluding publications falling outside the scope of Ti-based materials, advanced manufacturing routes, or the enhancement of surface integrity and functional performance.

2.2. Study Selection and Screening

The identification and selection of relevant studies were conducted in accordance with the PRISMA 2020 guidelines, thereby ensuring methodological transparency, traceability, and reproducibility throughout the review process. The initial bibliographic search was carried out across the Web of Science, Scopus, and CrossRef databases and retrieved a substantial body of records published between 2010 and 2025. The large volume of initial results reflects, in part, the broad indexing coverage of CrossRef and related metadata repositories, which frequently include duplicate entries arising from publisher-level indexing, early-access records, and overlaps between databases.

To address these redundancies, an automated consolidation procedure was implemented using a bespoke MATLAB[®] script, supplemented by manual verification. This procedure harmonised bibliographic metadata across the different sources and enabled the systematic removal of duplicate records. The resulting dataset was then subjected to preliminary screening.

Screening and eligibility decisions were subsequently undertaken in accordance with predefined inclusion and exclusion criteria established prior to database interrogation, with the objective of minimising subjective bias and ensuring methodological consistency. Titles, abstracts, and keywords were examined in order to assess their relevance to Ti-alloys and their processing routes, with particular emphasis on AM, hybrid manufacturing, and post-processing operations. Specific attention was directed towards studies addressing alloy classes and compositions, process–structure–property relationships, dimensional accuracy, residual stress development, surface integrity, heat treatment, hot isostatic pressing, machining, and the mechanical performance of Ti components produced through advanced manufacturing routes.

Publications lacking methodological clarity, those unrelated to Ti-based materials, or studies that did not address additive, hybrid, or post-processing aspects of Ti manufacturing were excluded at this stage. A considerable proportion of the discarded literature concerned either general metallic processing with no specific relevance to Ti-alloys, or conventional forming and machining routes without substantive connection to additive or hybrid manufacturing strategies.

The final stage involved a detailed full-text assessment of the remaining studies in order to determine their methodological robustness, industrial relevance, and conceptual coherence with the objectives of the present review. Following application of the established eligibility criteria, the final corpus comprised peer-reviewed publications considered sufficiently rigorous and relevant to support the analytical framework of the study. As a limited number of journals accounted for a disproportionately large share of the retrieved literature, scientific relevance, technical depth, and citation influence were also considered so as to reduce potential publication-source bias. The resulting dataset therefore represents a curated body of literature encompassing the most influential and methodologically robust studies concerning the production, AM, hybrid processing, and post-treatment of Ti-alloys.

During the review process, a recurrent challenge concerned the absence of fully standardised terminology within the Ti manufacturing literature. Identical or closely related processes are frequently described using different nomenclature, particularly in the case of additive technologies and hybrid process chains. For example, laser powder bed fusion may also appear as selective laser melting, and hybrid manufacturing may be described as hybrid additive–subtractive manufacturing or integrated additive–machining systems. Comparable inconsistencies arise in relation to post-processing terminology, where expressions such as post-processing, post-treatment, finishing, thermal treatment, and surface modification are not always used with strict definitional consistency. These variations required careful cross-verification of process descriptions, alloy systems, and post-treatment routes during the classification and interpretation of the retrieved studies. Minor orthographic differences between American and British English, such as mold/moulding and machining/machining-related usage conventions in indexed metadata, introduced further bibliographic inconsistencies.

The formulation of precise research questions constitutes a fundamental element of any systematic literature review, as it defines the analytical scope and conceptual direction of the investigation. To ensure internal coherence

and close alignment with contemporary developments in Ti-alloy processing, the Population–Intervention–Comparison–Outcome–Context (PICOC) framework was adapted for the present study as follows:

- Population: Experimental, numerical, and review studies concerned with Ti and Ti-alloy systems, especially those addressing Ti-6Al-4V and related near- α , $\alpha + \beta$, and β alloys, across conventional, additive, and hybrid manufacturing routes.
- Intervention: Advanced manufacturing and post-processing strategies applied to Ti-alloys, including powder bed fusion, EBM, directed energy deposition, wire arc additive manufacturing, hybrid additive–subtractive manufacturing, heat treatment, hot isostatic pressing, machining, and surface-finishing operations intended to improve dimensional accuracy, microstructural control, and service performance.
- Comparison: Comparative analyses between conventional and additive routes, between additive and hybrid manufacturing strategies, and between as-built and post-processed conditions, particularly with respect to microstructure, residual stress, surface integrity, fatigue behaviour, dimensional tolerance, and overall manufacturability.
- Outcomes: Improvements in material utilisation, geometric complexity, dimensional accuracy, surface quality, residual-stress mitigation, microstructural refinement, fatigue resistance, mechanical performance, and process efficiency, together with the identification of persistent manufacturing limitations and unresolved research challenges in Ti-alloy processing.
- Context: Peer-reviewed academic and industrial publications addressing Ti-alloys, AM, hybrid manufacturing, and post-processing technologies, published between 2010 and 2025.

Based on this framework, a structured and hierarchically organised set of research questions was established to guide the systematic extraction, critical evaluation, and synthesis of the knowledge contained within the selected literature. These research questions are presented in Table 7 of the manuscript.

Table 7 defines the research questions guiding the review and shows that the analysis is centred on the relationship between manufacturing route, post-processing, and final Ti-alloy performance. The present review considered peer-reviewed publications published between 2010 and 2025, with particular emphasis placed on contributions from the most recent decade addressing the production, AM, hybrid processing, and post-processing of Ti-alloys. This timeframe was selected in order to capture the rapid technological developments that have taken place in advanced Ti manufacturing, particularly with respect to powder bed fusion, EBM, directed energy deposition, wire arc additive manufacturing, hybrid additive–subtractive systems, and associated post-treatment operations. Particular attention was devoted to studies examining process–structure–property relationships, residual-stress development, dimensional accuracy, surface integrity, machinability, and the mechanical performance of Ti-alloy components.

The literature search procedure, as illustrated in Figure 4, was implemented using structured Boolean queries designed to identify studies situated at the intersection of Ti-alloy systems, advanced manufacturing routes, and post-processing methodologies.

The search strategy therefore incorporated combinations of keywords related to titanium materials and alloy classes, including “Ti-alloys”, “ α titanium alloys”, “ $\alpha + \beta$ titanium alloys”, “ β titanium alloys” and “ γ titanium alloys”, together with terms associated with advanced manufacturing technologies, such as “Additive manufacturing”, “Selective Laser Melting”, “Electron Beam Melting”, “Directed Energy Deposition”, “Wire Arc Additive Manufacturing”, and “Hybrid manufacturing”. A third group of terms addressed post-processing and performance-related considerations, including “Post-processing”, “Heat treatment”, “Hot Isostatic Pressing”, “Machining”, “Surface finishing”, “Residual stress”, and “Surface roughness”.

This structured search approach enabled the targeted retrieval of scientific contributions directly concerned with the manufacture and subsequent enhancement of Ti-alloy components, with relevance to studies addressing defect formation, microstructural control, process optimisation, residual-stress mitigation, surface-quality improvement, and the integration of additive and subtractive stages within hybrid manufacturing routes. In this way, the search strategy was designed to support a technically rigorous assessment of the principal challenges and emerging opportunities associated with the production and post-treatment of Ti-alloys for high-performance engineering applications.

An examination of publication records indexed within the CrossRef repository reveals a marked increase in scholarly output between 2010 and 2025, as illustrated in Figure 5. This upward trend reflects the growing academic and industrial attention devoted to the manufacture and post-processing of Ti-alloys, particularly within the context of additive and hybrid manufacturing technologies. The sustained rise in publications highlights the expanding interest in process optimisation, microstructural control, residual-stress mitigation, surface-integrity

enhancement, and the improvement of mechanical performance, especially for high-value Ti components intended for demanding engineering applications.

Collectively, these developments underscore the growing recognition of additive and hybrid manufacturing, in conjunction with appropriate post-processing strategies, as key enabling approaches for advancing the efficiency, precision, and functional performance of Ti-alloy components in contemporary high-performance manufacturing environments.

Table 7. PICOC RQ's.

ID	Research Question
RQ1	What are the principal manufacturing and post-processing challenges affecting the quality, reliability, and functional performance of Ti-alloy components produced by additive and hybrid manufacturing routes?
RQ1.1	How do defect formation mechanisms—such as porosity, lack of fusion, residual-stress-induced distortion, oxidation, surface damage, and microstructural anisotropy—manifest in additively manufactured Ti-alloys, and how do they influence subsequent post-processing operations?
RQ1.2	Which material characteristics and processing variables, including alloy composition, thermal history, scan strategy, energy input, cooling conditions, and shielding atmosphere, exert the greatest influence on microstructure, surface integrity, dimensional accuracy, and mechanical performance in Ti-alloy components?
RQ2	How do post-processing operations determine the final quality and performance of Ti-alloy components manufactured through additive and hybrid routes?
RQ2.1	To what extent do post-processing routes—such as stress-relief heat treatment, hot isostatic pressing, machining, and surface-finishing operations—enhance the fatigue behaviour, residual-stress state, dimensional precision, and surface quality of Ti-alloy parts?
RQ2.2	What are the principal trade-offs associated with post-processing Ti-alloys, particularly in relation to cost, productivity, TW, material removal requirements, and the preservation of surface and subsurface integrity?
RQ3	How do process parameters, machine configurations, and manufacturing-route selection influence the stability, repeatability, and overall robustness of additive and hybrid manufacturing operations for Ti-alloys?
RQ3.1	Which process variables—such as build orientation, layer thickness, laser or beam power, feed rate, deposition strategy, machining allowance, and cutting parameters—most strongly affect geometric accuracy, residual stress development, and surface integrity in Ti-alloy manufacture?
RQ3.2	How does the integration of additive and subtractive stages within hybrid manufacturing systems influence process efficiency, tolerance control, and the mitigation of defects associated with near-net-shape Ti components?
RQ4	What recent developments in digital manufacturing technologies, modelling approaches, and process-monitoring tools contribute to improved process understanding and optimisation in the additive and hybrid manufacture of Ti-alloys?
RQ4.1	How can computational modelling, thermo-mechanical simulation, and data-informed predictive tools support the optimisation of process parameters, distortion compensation, residual-stress control, and machining strategy selection for Ti-alloy components?
RQ4.2	What technical and industrial limitations currently hinder the broader implementation of simulation-driven optimisation, in-situ monitoring, and digitally assisted process planning in Ti-alloy manufacturing environments?
RQ5	What are the emerging research trends and future opportunities in the manufacture and post-processing of Ti-alloys through additive and hybrid approaches?
RQ5.1	Which advanced manufacturing concepts—such as hybrid additive–subtractive platforms, in-situ monitoring, closed-loop control, digital twins, and integrated post-processing strategies—show the greatest potential for improving the quality and industrial viability of Ti-alloy components?
RQ5.2	What key knowledge gaps remain regarding the integration of alloy design, additive processing, hybrid manufacturing, and post-processing science in the development of next-generation Ti-alloy systems?

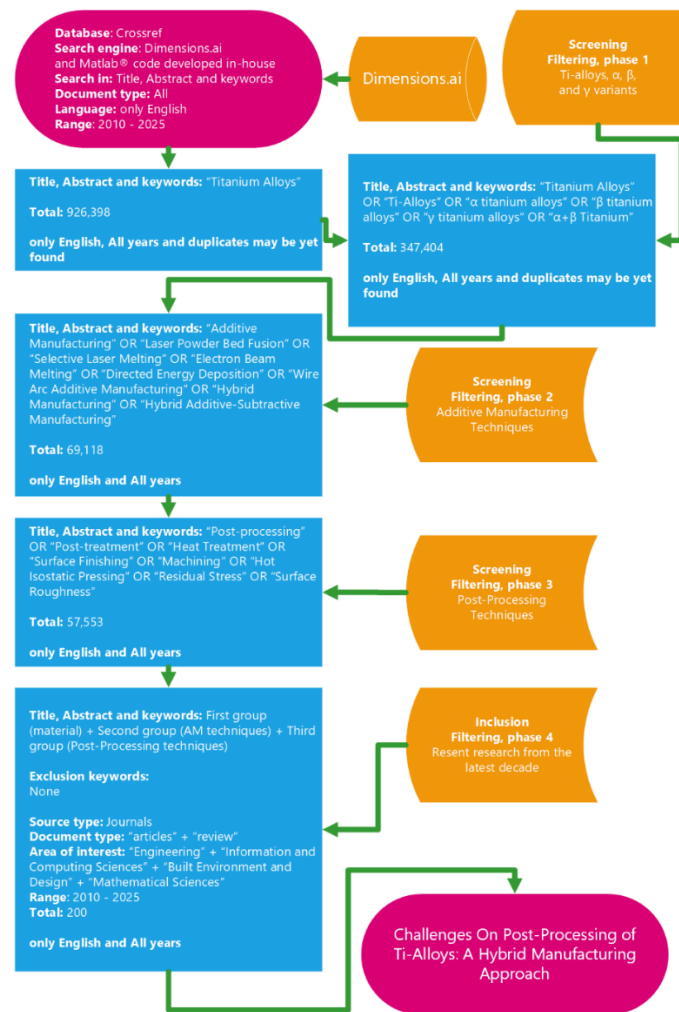


Figure 4. PRISMA-based multi-stage screening and study selection procedure applied to the literature concerning Ti-alloys, with emphasis on AM, hybrid manufacturing, and post-processing routes.

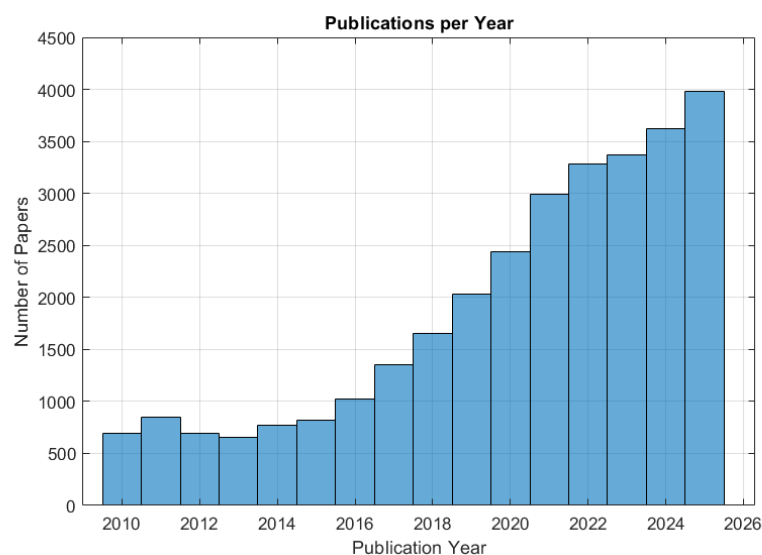


Figure 5. Annual distribution of publications retrieved from the CrossRef database concerning Ti-alloys, with emphasis on AM, hybrid manufacturing, and post-processing routes.

2.3. Study selection and Quality Assessment (QA)

The appraisal of methodological quality represents an essential component of any systematic review, since the credibility of the ensuing synthesis depends directly upon the reliability, transparency, and analytical strength

of the studies included. In the present investigation, a structured Quality Assessment (QA) procedure was established to evaluate the scientific rigour, reporting clarity, and technical relevance of each selected publication. The assessment strategy was conceived as a multidimensional framework capable of capturing not only academic robustness, but also the extent to which the reported findings contribute meaningfully to the understanding and advancement of Ti-alloy manufacturing through additive, hybrid, and post-processing routes.

The QA framework was organised into four equally weighted domains, each intended to examine a distinct dimension of methodological quality and scholarly contribution. The criteria were informed by established principles for systematic review design and were applied through a three-level ordinal scoring system, in which Yes was assigned 1, Partly 0.5, and No 0.

The four evaluation domains were defined as follows:

- Research Design and Conceptual Coherence (25%)—assessing the clarity of the study aims, the suitability of the research methodology, and the extent to which the investigation is supported by a coherent scientific and technical rationale.
- Definition of Material System and Processing Conditions (25%)—examining whether the Ti-alloy under study, the manufacturing route, and the relevant processing parameters are described with sufficient precision, including details necessary for reproducibility, such as thermal history, energy input, build strategy, machining conditions, or post-treatment parameters.
- Methodological Rigour and Analytical Transparency (25%)—evaluating the robustness of the experimental, numerical, or analytical procedures, the adequacy of validation methods, and the consistency with which data interpretation is conducted and reported.
- Technological and Industrial Relevance (25%)—determining the degree to which the findings contribute to the practical understanding of Ti-alloy manufacture, particularly in relation to process optimisation, residual-stress mitigation, dimensional control, surface integrity, machinability, and component performance.

To preserve the reliability of the final synthesis, only studies achieving a QA score above 50%, corresponding to a total score exceeding 5 out of 10, were retained for detailed analysis, as illustrated in Figure 6. The use of this threshold made it possible to exclude contributions with inadequate methodological clarity whilst avoiding the unnecessary removal of studies addressing emerging manufacturing and post-processing strategies, where reporting practices may differ across experimental and modelling-based investigations. The QA procedure therefore functioned as a baseline filter for methodological dependability, ensuring a consistent evidential standard while maintaining appropriate breadth in the range of technological approaches represented within the review.

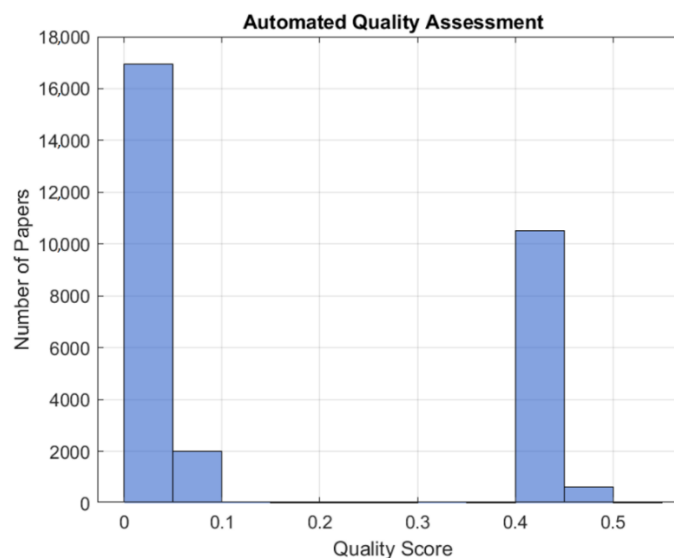


Figure 6. QA outcomes for the selected publications included in the systematic review of Ti-alloys in AM, hybrid manufacturing, and post-processing.

Publications achieving scores near the predefined inclusion threshold were subjected to a further stage of qualitative appraisal in order to confirm their technical relevance, methodological integrity, and consistency with the aims of the present review. This supplementary scrutiny ensured that studies falling within the marginal range nonetheless provided an adequately clear account of the Ti-alloy investigated, the manufacturing route employed, the post-processing strategy adopted, and the principal outcomes reported. As a result, the final corpus of literature

consisted exclusively of contributions demonstrating an acceptable standard of methodological soundness, technical relevance, and conceptual alignment with the review objectives, particularly in relation to AM, hybrid manufacturing, post-processing, residual-stress mitigation, surface integrity, and mechanical performance in Ti-alloy systems.

Studies with QA scores within the borderline interval of 50–60% were re-examined through detailed full-text assessment undertaken by the authors. This stage focused on verifying the adequacy with which processing conditions, alloy designations, manufacturing parameters, post-treatment procedures, and performance indicators had been reported. The purpose of this additional assessment was to ensure that only studies offering substantive and technically meaningful insight into the manufacture and post-processing of Ti-alloys were retained within the final analytical synthesis.

The identification and selection of relevant publications followed a three-stage screening procedure consistent with the PRISMA 2020 framework, thereby ensuring a transparent and methodologically systematic progression from the initial retrieval of records to the final inclusion of eligible studies. In the first stage, all search results were consolidated into a single dataset, and duplicate records were removed through a combination of automated processing and manual verification using the customised MATLAB® routine described previously.

As illustrated in Figure 7, the geographical distribution of authorship and institutional affiliation within the reviewed literature indicates a marked concentration of research activity in regions with established strengths in advanced manufacturing and high-performance materials engineering. Asia emerges as a particularly significant contributor, with China occupying a prominent position within the scholarly output relating to Ti-alloys, AM, hybrid manufacturing, and associated post-processing technologies. A substantial proportion of the analysed publications also originates from the United States, reflecting the industrial importance of Ti-based manufacturing in sectors such as aerospace, biomedical engineering, and other high-value applications requiring demanding combinations of strength, precision, and material performance.

This geographical pattern is of relevance, as it indicates that research into the manufacture and post-treatment of Ti-alloys is not confined to a narrow set of countries traditionally associated with metallurgical or manufacturing innovation. Rather, the field exhibits an increasingly international and collaborative research profile, reflecting the global significance of efforts to improve process efficiency, dimensional control, surface quality, microstructural stability, and the overall functional performance of Ti-alloy components through advanced additive, hybrid, and post-processing methodologies.

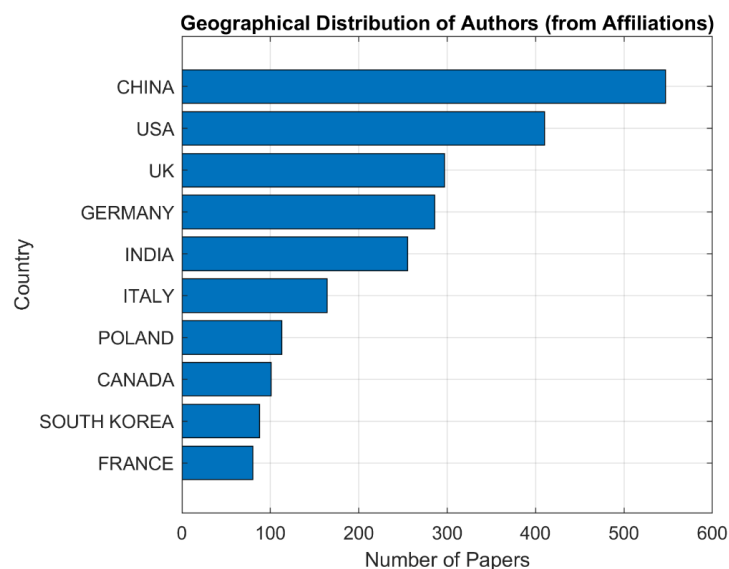


Figure 7. Geographical distribution of authors' institutional affiliations within the publications included in the systematic review Geographical distribution of authorship and institutional affiliations within the reviewed literature concerning Ti-alloys, with emphasis on AM, hybrid manufacturing, and post-processing routes.

2.4. Descriptive Analysis and Taxonomic Synthesis

The descriptive synthesis of the final body of literature reveals a technically diverse and steadily expanding field of research, characterised by the growing convergence of Ti-alloy metallurgy, advanced manufacturing science, and post-processing engineering. The selected studies were classified according to their technological orientation, application emphasis, and level of experimental, numerical, or integrated process analysis, thereby

enabling the identification of the principal trajectories along which contemporary research on Ti-alloy manufacture is developing. Overall, the reviewed literature may be understood as converging around two closely related research domains.

1. **Additive and hybrid manufacturing of Ti-alloys:** This domain encompasses investigations concerned with the production of Ti-alloy components through additive routes and integrated hybrid manufacturing systems. Particular attention is given to the influence of process conditions on deposition behaviour, thermal cycling, layer consolidation, geometric accuracy, and process stability. Studies within this category examine the effects of variables such as energy density, scan strategy, layer thickness, feed rate, build orientation, shielding conditions, and deposition path on the formation of microstructural features, internal defects, and residual stresses. Research in this area is directed towards improving the reliability, repeatability, and manufacturability of Ti-alloy components produced by near-net-shape routes.
2. **Post-processing and performance enhancement:** The second domain concerns the post-manufacture treatment of Ti-alloy components with the aim of improving their structural integrity and service performance. This body of work includes studies focused on heat treatment, hot isostatic pressing, machining, and surface-finishing operations, together with investigations into their influence on residual stress redistribution, porosity reduction, dimensional correction, surface integrity, and fatigue resistance. These approaches are intended to overcome the limitations of as-built material states and to enable the production of Ti components meeting the stringent requirements of high-performance engineering sectors.

This classification highlights the inherently multidisciplinary character of current research in Ti-alloy manufacturing, where materials science, manufacturing engineering, surface engineering, and process optimisation intersect in order to address the complex thermal, mechanical, and metallurgical phenomena associated with additive and hybrid production routes. Across the reviewed literature, four principal thematic directions may be distinguished.

1. **Defect formation and quality enhancement:** A substantial proportion of the literature is devoted to the identification, characterisation, and mitigation of common manufacturing defects, including porosity, lack of fusion, residual-stress-induced distortion, surface irregularities, and microstructural anisotropy. These studies seek to clarify the relationships between process conditions, defect generation, and final component performance, with the objective of improving manufacturing reliability and reducing the need for excessive corrective post-treatment.
2. **Process-parameter optimisation:** Another major line of investigation concerns the optimisation of manufacturing variables in order to improve build quality, dimensional accuracy, and process efficiency. Particular emphasis is placed on the selection of parameter combinations capable of controlling heat input, cooling behaviour, material consolidation, and surface formation. In the case of hybrid manufacturing, additional attention is paid to the interaction between additive deposition and subsequent subtractive operations, especially where machining allowance, tolerance control, and sequence planning are concerned.
3. **Residual stress, microstructure, and mechanical performance:** Recent studies increasingly examine the interdependence between process-induced thermal histories, phase evolution, residual stress accumulation, and the resulting mechanical behaviour of Ti-alloys. This includes analyses of tensile strength, fatigue resistance, hardness, ductility, and fracture behaviour, as well as investigations into the extent to which post-processing routes can refine microstructure and improve performance consistency.
4. **Digital modelling and simulation-assisted manufacturing:** A further area of development involves the use of computational modelling and simulation tools to improve process understanding and support manufacturing optimisation. These studies address thermo-mechanical prediction, distortion compensation, residual stress estimation, process planning, and the digital evaluation of manufacturing strategies, thereby contributing to more reliable and scalable production of Ti-alloy components.

Across the reviewed studies, several recurrent performance gains are reported, including:

- improved dimensional accuracy and geometric conformity;
- enhanced surface quality and reduced roughness following finishing operations;
- mitigation of residual stresses and associated distortion;
- refinement of microstructure and reduction of internal defects through appropriate thermal and pressure-assisted post-treatments;
- improved fatigue behaviour and overall mechanical performance;
- greater process efficiency and material utilisation through near-net-shape manufacturing routes.

Notwithstanding these advances, the literature also identifies a number of persistent challenges that continue to limit broader industrial implementation. These include the difficulty of achieving consistent process repeatability, the complexity of controlling thermal histories and residual-stress development, the high reactivity and poor machinability of Ti-alloys, and the need for substantial post-processing in order to satisfy demanding dimensional and surface-quality requirements. Additional constraints arise from the limited standardisation of process qualification procedures, the variability of reported parameter sets across different platforms, and the continuing challenge of integrating additive, hybrid, and post-treatment stages into coherent and economically viable manufacturing chains.

The three-stage screening procedure adopted in the present review, in accordance with the PRISMA 2020 framework, commenced with an initial appraisal of titles, abstracts, and keywords in order to identify publications relevant to Ti-alloys, AM, hybrid processing, and post-processing technologies. This preliminary screening was followed by detailed full-text assessment designed to verify conformity with the predefined inclusion criteria, with particular emphasis placed on methodological rigour, technical depth, and relevance to the objectives of the review.

Only peer-reviewed journal articles were retained for the final analysis. Publications written in languages other than English, grey literature, conference abstracts lacking adequate methodological detail, and studies without sufficiently transparent analytical procedures were excluded. The resulting dataset therefore constitutes a carefully curated and scientifically robust body of literature, providing the evidential foundation for the analytical and interpretative framework developed in the present study.

3. Literature Review

In line with the process-chain perspective introduced in Section 1, the literature review does not consider AM routes as self-contained manufacturing solutions. Instead, each process is examined in relation to the downstream operations required to achieve final component performance, including heat treatment, hot isostatic pressing, machining, surface finishing, and dimensional correction. This framing is necessary because the performance of Ti-alloy components is determined not only by the initial manufacturing route, but also by the integration between deposition, thermal history, defect mitigation, surface integrity control, and post-processing strategy. AM comprises a diverse and rapidly evolving group of technologies that differ significantly in energy source, feedstock delivery, deposition mechanism, and processing environment. This diversity is particularly relevant to Ti-alloys, since manufacturing route selection strongly influences microstructural development, defect formation, dimensional accuracy, surface integrity, and post-processing requirements.

Figure 8 provides a structured overview of the principal technological families within AM and offers a useful conceptual starting point for the literature review. As illustrated, AM encompasses a broad and heterogeneous set of processes that may be grouped into two overarching categories: beamless methods and beam-based methods. Beamless routes include approaches such as BJ, material jetting, sheet lamination, material extrusion, cold spray AM, additive friction stir deposition, and related solid-state or droplet-based techniques. Beam-based routes, by contrast, rely on concentrated thermal energy sources and include the two process families most widely discussed in the manufacture of Ti-alloys, namely powder bed fusion (PBF) and directed energy deposition (DED).

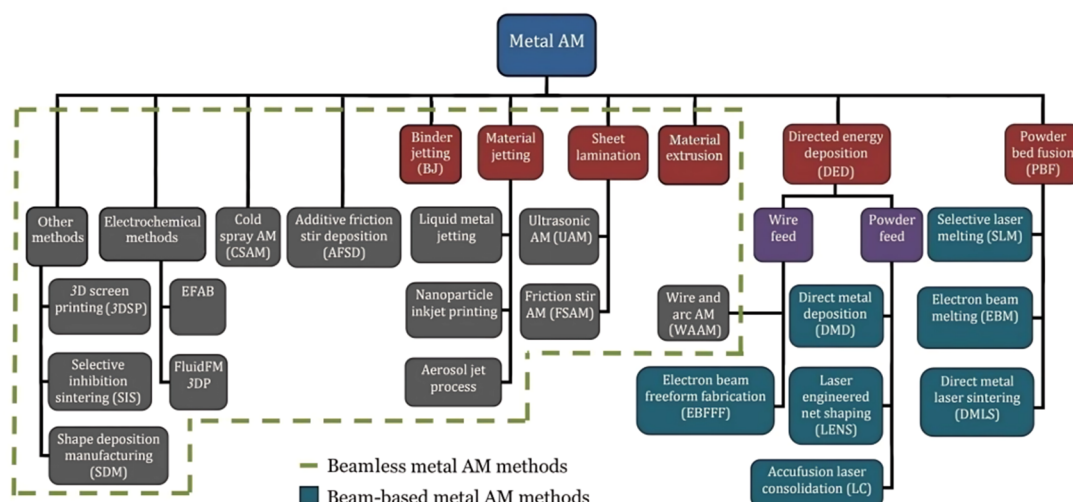


Figure 8. Schematic classification of AM processes, highlighting the distinction between beam-based and beamless process families [99].

Within these categories, the figure highlights the relevance of selective laser melting (SLM), electron beam melting (EBM), and wire arc additive manufacturing (WAAM), which have emerged as some of the most significant technologies to produce Ti-alloy components. Their prominence arises from the ability to fabricate geometrically complex structures, reduce material waste, and support near-net-shape manufacturing for high-value sectors such as aerospace, biomedical engineering, and defence. At the same time, the diversity of these process routes also explains the broad variation observed in thermal histories, solidification behaviour, residual-stress development, surface quality, and final mechanical performance.

In this context, the following subsections present a structured overview of the principal and most used techniques currently employed in the AM of Ti-alloys. For the sake of clarity and consistency, the processes are introduced in alphabetical order, whilst maintaining emphasis on their technological principles, processing characteristics, material implications, and relevance to industrial application. This organisation is intended to facilitate a systematic comparison of the different manufacturing routes and to clarify how each technique influences microstructural evolution, defect formation, surface quality, and post-processing requirements. Collectively, these subsections provide the foundation for the subsequent discussion of performance, limitations, and future development within the field.

3.1. Binder Jetting (BJ)

BJ represents a comparatively distinct route within Ti-alloys AM, as its viability depends not only on the build stage itself, but also on the effectiveness of the subsequent thermal and densification treatments required to obtain structurally reliable components.

Table 8 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of BJ as a manufacturing route for Ti-alloy components. The reader might find that BJ of Ti-alloys is strongly dependent on debinding, sintering, HIP, and finishing operations, making post-processing decisive for density, dimensional stability, and final performance.

Table 8. Representative studies on Ti-alloy materials manufactured by BJ.

Ref	Material	Technique	Challenges/Highlights
[100]	Commercially pure Grade 1 Ti ASTM B 348	BJ, followed sintering	Shrinkage and anisotropic densification/Sintering behaviour were strongly governed by powder-size distribution; finer particles improved densification, but segregation effects introduced significant local density fluctuations and anisotropic post-sinter behaviour.
[101]	Commercially pure Grade 1 Ti ASTM B 348	PBBJ + sintering	Non-homogeneous densification and pore segregation/Post-sinter CT analysis showed that densifying sintering improved relative density, but powder-size distribution strongly governed pore structure and could still produce heterogeneous internal architectures.
[102]	Ti-22Al-25Nb	BJ of Ti, Al, and Nb elemental powders, + curing, sintering, and annealing	Persistent high porosity after annealing/Reactive sintering and subsequent annealing at 1400 °C promoted B2/ β -solid solution and acicular Ti ₂ AlNb precipitates, increasing density and strength, although substantial residual porosity (~40%) remained.
[103]	Commercially pure Grade 1 Ti ASTM B 348	BJ + debinding + sintering under master sinter curve control	Anisotropic shrinkage during post-sinter densification/For BJed CP Ti, the master sinter curve predicted sintered density with 0.9–4.3% error, showing a clear value for designing HT schedules despite orientation-dependent densification behaviour.
[104]	Ti-6Al-4V	BJ + curing + debinding + sintering	Debinding reactions hinder full densification/Post-processing by vacuum sintering at 1420 °C for 2 h, combined with mixed fine powder, increased density to 95.2% and improved hardness (316 HV), and tensile performance (589 MPa yield stress).
[105]	Ti-6Al-4V	BJ for medical metal parts and implants	Limited strength; sparse post-processing detail/The review identifies Ti-based materials within BJ implants and notes that AM components often require post-processing, yet no BJ Ti-specific finishing route is described.
[106]	Ti-6Al-4V	BJ, followed by deburring, grinding, and polishing	Poor fit and rough surface/Post-processing improved handling, yet the Ti framework remained rough and lacklustre after polishing, and its fit was still not clinically acceptable for removable partial denture application.

Table 8. *Cont.*

Ref	Material	Technique	Challenges/Highlights
[107]	Ti-alloy for biocompatible implant and dental applications	BJ + sintering. Also includes HIP, infiltration, grinding, and polishing	Shrinkage control and porosity reduction/The review identifies post-processing as the principal determinant of final performance: sintering increases density and strength, HIP reduces porosity and grinding/polishing improve surface condition and dimensional outcome.
[108]	INCONEL® 718/TiC	BJ + Sintering + HIP + HT	Post-sinter residual porosity requiring HIP densification/HIP followed by heat treatment markedly improved densification and hardness in TiC-containing specimens, with best tensile performance at 3 wt.% TiC and best wear resistance at 5 wt.% TiC.
[109]	Ni–Ti Ni50.8Ti49.2	BJ + vacuum curing + solid-state sintering	Residual porosity, secondary phases and C-contamination/Post-sintering at 1185 °C reduced pore volume from ~15% to ~5%, increased hardness, and improved densification, although TiC-, Ni3Ti-, and Ni4Ti3-related phase evolution remained evident, affecting phase stability and transformation behaviour.
[110]	Ti-6Al-4V	BJ + curing before depowdering + sintering	Non-uniform curing and fragile green parts/For Ti-6Al-4V BJ components, extended curing holding times improved green strength and depowderability, whilst short ramp times remained feasible; positional curing non-uniformity was also identified.

Caption: HIP—Hot isostatic pressing, HT—Heat Treatment, MMC—Metal-Matrix Composite, PBBJ—Powder bed BJ, wt.%—weight content.

3.2. Direct Energy Deposition (DED)

DED occupies a particularly important position within Ti-alloy manufacturing, owing to its suitability for near-net-shape fabrication, large-scale component production, and repair applications, whilst simultaneously presenting notable challenges in geometric accuracy, thermal control, surface integrity, and the extent of post-processing required to achieve final functional performance.

Table 9 compiles representative studies published between 2010 and 2025, together with their respective processing parameters and principal findings, thereby offering a comprehensive overview of the evolution of DED for the manufacture of Ti-alloy components. The reader will find that DED is attractive for repair and near-net-shape Ti-alloy fabrication, but geometric accuracy, thermal control, and surface integrity remain major post-processing drivers.

Table 9. Representative studies on Ti-alloy materials manufactured by DED.

Ref	Material	Technique	Challenges/Highlights
[111]	Ti-6Al-4V	LDED + HIP + HT	Martensitic structure and ductility loss/Post-processing by HIP at elevated temperature and pressure densified DED Ti-6Al-4V, promoted α -lath coarsening, reduced brittleness, and increased elongation at break.
[112]	Ti–Ta porous coating on Ti-6Al-4V	DED + anodic oxidation	Surface bioactivity requires enhancement/DED-enabled deposition of a porous Ti–Ta coating on Ti-6Al-4V; anodic oxidation generated Ti/Ta oxide nanotubes, induced apatite formation, and promoted osteoblast adhesion and bone formation.
[113]	Ti-6Al-4V, deposited on a tool-steel substrate	DED specimens sectioned for microscopy and topography assessment	Surface defects before any finishing/The study links DED parameter variation to surface topography, porosity, lack-of-fusion features, and cracking, showing strong value for in-situ quality control rather than post-processing optimisation.
[114]	Ti-6Al-4V	LDED under controlled reactive Argon (Ar)	Interstitial pickup and ductility loss/No separate post-processing treatment was applied; however, intrinsic thermal cycling during DED promoted in-situ martensite decomposition to lamellar $\alpha + \beta$ phase, whilst recycled powder increased strength but reduced ductility.
[115]	Ti-22Al-25Nb	DED LMD + HT + point-forging	Cracking susceptibility and brittle microstructure/For DED Ti-22Al-25Nb, post-processing through heat treatment and thermomechanical point forging was reported to refine strengthening phases, increase hardness, and achieve ductility above 25%.
[116]	Ti-6Al-4V deposited on AISI 410, AISI 304L, and AISI 316L substrates	DED + machining + HT	Brittle Ti–Fe intermetallic cracking/For Ti–Fe DED systems, post-processing is framed as supportive rather than primary: machining addresses poor geometric resolution, while HT helps reduce residual stresses after deposition.
[117]	Ti-6.5Al-3.5Mo-1.5Zr-0.3Si/ Ti-6Al-4V	LDED + ST @ 1005 °C and HT @ 530 °C	TC4-side strain localisation after HT/Post-HT preserved comparable strength and ductility, refined interfacial mechanical stability, and maintained a crack-resistant graded interface, although final failure still occurred in the Ti-6Al-4V region.

Table 9. Cont.

Ref	Material	Technique	Challenges/Highlights
[118]	Ti-6Al-4V	LDED + forging + HT (annealing)	HAZ heterogeneity and grain coarsening/Post-deposition HT improved the hybrid-manufactured TC4 response; 600 °C annealing gave the best strength, whereas double annealing at 975 °C markedly coarsened HAZ grains.
[119]	Ti25-Fe9-Al66 and Ti25-Fe16-Al59 Ti-trialuminide-based alloys	LDED; no post-processing experimentally applied	Unmelted particles and brittle phases/The study shows that as-deposited Ti25-Fe9-Al66 developed a refined dendritic L1 ₂ microstructure with improved fracture toughness, whereas higher Fe promoted brittle secondary phases; post-HT is only suggested in relation to unmelted particles.

Caption: HAZ—Heat-Affected Zone, LDED—laser direct energy deposition, LMD—laser melting deposition, ST—Solution treatment.

Wire Arc Additive Manufacturing (WAAM)

WAAM has emerged as one of the most industrially attractive routes for Ti-alloy fabrication, particularly for large and high-deposition-rate components, although its broader implementation continues to be constrained by limitations in dimensional accuracy, surface quality, thermal management, and the substantial post-processing needed to achieve final specification.

Table 10 compiles representative studies published between 2010 and 2025, together with their respective processing parameters and principal findings, thereby offering a comprehensive overview of the evolution of WAAM for the manufacture of Ti-alloy components. From Table 10 WAAM offers high deposition rate and large-build capability for Ti-alloys, but usually requires HT, inter-layer conditioning, machining, or finishing to achieve stable final properties.

Table 10. Representative studies on Ti-alloy materials manufactured by WAAM.

Ref	Material	Technique	Challenges/Highlights
[120]	Ti-47Al	WAAM + GMAW + HT @ 1180 °C for 4–12 h	Dendritic segregation and cold cracks/Heat treatment above the eutectoid temperature improved Ti-47Al microstructural uniformity, reducing dendritic γ regions and promoting fine lamellar $\alpha_2 + \gamma$ duplex regions after 8–12 h.
[121]	Ti-6Al-4V	PAW-WAAM, + HT @ 720 °C for 2.5 h + drilling	Higher drilling forces after WAAM/Post-deposition stress relief and finish machining enabled WAAM Ti-6Al-4V to satisfy mechanical-property requirements and achieve lower burr height, although drilling torque and thrust force remained higher.
[122]	Ti Grade 2 and pure Fe wire on a CP-Ti Grade 2 substrate	GTWAW-WAAM	Substrate dilution and compositional gradient/The study demonstrated successful as-fabricated Ti-Fe wall production by WAAM, achieving the target composition in the upper zone, but without a distinct post-processing stage beyond metallographic preparation.
[123]	Ti-6Al-4V $\alpha + \beta$ Ti-alloy	WAAM + EBM + HT @ 710 °C for 2 h	Residual stress and lack of fusion/PWHT decomposed the as-deposited martensitic/fine- α structure into fine $\alpha + \beta$ lamellae, reduced tensile residual stresses from 200–450 MPa to near-zero, and improved elongation from 4.5% to 9.5%.
[124]	Grade II pure Ti	GMA-WAAM	Arc instability and bead waviness/Inter-layer oxide brushing and surface-treated wire improved arc stability, bead homogeneity, and enabled successful fabrication of thin-walled Ti structures.
[125]	Ti-6Al-4V	WAAM-CMT	Geometric instability and projection defects/No dedicated thermal post-processing was reported; however, parameter optimisation avoided weld-pool collapse and lack of fusion, and subsequent machining produced fully smooth thin walls of 3.0–3.7 mm thickness.
[126]	Ti-6Al-xV Ti-alloys	WAAM	Toughness loss with higher V/T he review reports that increasing vanadium content raised yield and ultimate tensile strength, but reduced fracture strain and impact toughness, while producing irregular plate-like microstructural features without columnar grains.
[127]	Ti-6.5Al-3.5Mo-1.5Zr-0.3Si	WAAM + HT @ 1263 K for 1 h + HT @ 803 K for 6 h	Residual strain and coarse β grains/Post-deposition annealing homogenised the WAAMed microstructure into a basket-weave morphology and improved plasticity, although some reduction in yield strength was observed after heat treatment.
[128]	Ti-48Al γ -Ti-aluminide	Twin WAAM + HT @ 1150 °C for 2 h	High residual stresses after deposition/The post-production heat treatment partially relieved residual stresses, especially in the longitudinal direction, and converted interdendritic γ -TiAl into equiaxed γ -TiAl whilst maintaining the target Ti-48Al composition.
[129]	Ti-6Al-4V-8.5Cu	WAAM no separate post-processing treatment reported	Columnar β grains and anisotropy/In-situ Cu alloying Ti-6Al-4V refined prior β grains, generated nanoscale Ti ₂ Cu precipitates, and increased hardness and tensile strength, whilst largely preserving ductility in the as-deposited condition.
[130]	Ti-6.5Al-2Zr-1Mo-1V	DHWAAM + HT @ 600 °C for 2 h or HT @ 980 °C for 1 h	Strength–ductility trade-off after annealing/For DHWAAMed Ti-alloy, stress-relief annealing homogenised the α distribution and improved yield strength, whereas double annealing stabilised α P/ α S lamellae but generally reduced strength.

Table 10. Cont.

Ref	Material	Technique	Challenges/Highlights
[131]	Ti-6Al-4V	DHWAAM	Mechanical anisotropy and pore defects/Layer cooling refined the β -grain morphology towards short columnar and equiaxed structures, increased ultimate tensile strength by 6.5%, and reduced anisotropy relative to conventional continuous deposition.
[132]	Ti-6Al-4V	WAAM	Controlled gradient microstructure formation/The WAAM route enabled layerwise microstructural regulation through electromagnetic stirring, refining β grains and improving the hardness–ductility balance without a separate post-processing stage.
[38]	Ti-6Al-4V; Ti64–0.07B, Ti64–CoCrNi, Ti64–0.9Ni and variants	WAAM, with inter-pass rolling, IMHP, UIT, UPT, and LSP	Columnar β grains and anisotropy/WAAM+ post-processing is reported to refine coarse columnar β grains, reduce residual stress and anisotropy, and improve mechanical uniformity whilst enabling efficient one-step industrial production.
[133]	Grade II pure Ti	PHWAAM	Deposition inaccuracy; brittle rod fracture/Fractographic analysis showed predominantly quasi-cleavage fracture with limited plastic deformation, indicating that structural optimisation rather than post-processing governed the compressive response of the as-fabricated lattice.
[134]	Ti-6Al-4V and Ti-6.53Al-1.46Zr-3.48Mo- 0.3Si	Double-WAAM + HT + SA	Weak interface strength; local unfused pores/Post-processing, especially SA, homogenised composition and microstructure, weakened or eliminated interface morphology, and improved interfacial mechanical properties, particularly in the three-layer transitional condition.
[135]	HOC-Ti pure	GTAW-WAAM, + EDM + 1 h annealing and air cooling	Brittle machining at high oxygen/After annealing, WAAM HOC-Ti with 0.37 wt.% oxygen gave the best strength–ductility balance, reaching about 732 MPa UTS and 6.7% elongation; higher oxygen caused brittle machining-induced cracking
[136]	Ti-6Al-4V	WAAM + machining	Columnar grains and SR/The review indicates that post-machining is essential for WAAMed Ti-6Al-4V; controlled heat input and interpass temperature improve machinability, enabling $R_a < 1 \mu\text{m}$ and, in ultra-precision finishing, about $R_a \sim 0.1 \mu\text{m}$.
[137]	Ti–6.3Cu–2.2Fe–2.1Al	WAAM	Low ductility despite high strength/The as-built deposit achieved a columnar-to-equiaxed transition, fine Ti_2Cu precipitates, and 1039 MPa yield strength, but only 1.41% elongation; subsequent heat treatment was identified as necessary future work.
[138]	TC17 near- β Ti-alloy Ti-5Al-2Sn-2Zr-4Mo-4Cr	WLDED	Columnar grains and anisotropy control/Without subsequent post-processing, six-laser coaxial WLDED produced a predominantly equiaxed prior- β structure, nanoscale $\alpha + \beta$ lamellae, ultrahigh strength, and minimal in-plane mechanical anisotropy. Near-isotropic strength was achieved directly in the as-deposited state, avoiding the need for compositional modification or auxiliary treatment.
[139]	Ti-6Al-4V	WAAM + IPCR + UP + LSP + HT + finish machining	Columnar grains, anisotropy, residual stress/The review shows that post-processing is central to WAAM Ti-alloys: inter-pass deformation and allied treatments refine β/α structures, reduce porosity and residual stress, and improve strength, hardness, and mechanical uniformity.
[140]	Ti-6.5Al-3.5Mo-1.5Zr-0.3Si deposited on Ti-6Al-4V	WAAM + HT 550 °C @ 4 h, 970 °C @ 2 h + 550 °C @ 4 h 990 °C @ 2 h + 550 °C @ 4 h or 1020 °C @ 2 h + 550 °C @ 4 h	Optimising fatigue crack growth resistance/The 1020 °C post-HT produced equiaxed grains with fine colony/basket-weave microstructures, yielding the lowest fatigue crack growth rate and outperforming the LMDed TC4-DT benchmark.

Caption: CMT—Cold Metal Transfer, DHWAAM—Double-hot-wire wire arc additive manufacturing, GMAW—gas metal arc welding, GMA—Gas metal arc, GTWAW—gas tungsten wire arc welding, HOC—High-oxygen-content, IPCR—inter-pass cold rolling, LSP—Laser Shock Peening, PAW—plasma arc welding, PHWAAM—Pulse hot-wire arc additive manufacturing, SA—Solution-Ageing, UP—ultrasonic peening, WLDED—Wire-Laser Directed Energy Deposition.

3.3. Powder Bed Fusion (PBF)

PBF has become one of the most established manufacturing families for Ti-alloy components, owing to its capacity to produce intricate geometries with comparatively high precision, although its wider industrial deployment remains closely tied to the control of residual stress, microscopical heterogeneity, surface quality and post-processing demand.

Table 11 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of PBF as a manufacturing route for Ti-alloy components. Table 11 shows that PBF is one of the most mature AM routes for complex Ti-alloy components, although residual stress, porosity, and surface finish still make post-processing essential.

Table 11. Representative studies on Ti-alloy materials manufactured by PBF.

Ref	Material	Technique	Challenges/Highlights
[141]	Ti-24Al-25Nb-1Zr-1.4V-0.6Mo-0.3Si	L-PBF HT @ 950 °C for 2 h	Cold cracking and brittle O-phase/Post-annealing HT transformed the fully O microstructure into lamellar B ₂ + O, increasing tensile strength for the 600–700 °C builds, although performance remained below the best as-fabricated 980 °C condition.
[142]	Ti-6Al-4V	L-PBF	Poor wear resistance; low hardness/In the as-built condition, L-PBF produced >99% relative density and hardness up to 581 HV through in-situ TiC formation and matrix grain refinement.
[143]	Ti-6Al-4V deposited onto EN AW-5083	L-PBF	Intermetallic cracking at Al/Ti interface/No post-processing was introduced; under optimised LPBF conditions, Ti-6Al-4V-on-aluminium hybrids developed intermetallic layers below 2 µm and achieved interfacial tensile strengths up to 170 N/mm ² .
[144]	Grade II pure Ti	LPBF + HIP @ 730 °C or 950 °C	Strength loss after HIP coarsening/HIP reduced porosity and increased fatigue-crack-growth threshold but coarsened the α-grain structure and lowered tensile strength, with the 950 °C treatment producing the strongest coarsening effect.
[145]	Functionally graded Ti-Ta binary alloy	LPBF + GAP system;	Powder contamination and interface segregation/The study demonstrated horizontal Ti-Ta compositional grading by LPBF, but identified excess Ta contamination, incomplete interfacial mixing, dendritic segregation, and the need for further powder-clearing and parameter refinement.
[105]	Ti-6Al-4V / Ti64	PBF for patient specific implants	Support removal and finishing requirements/For patient-specific implants, Ti-6Al-4V/Ti64 components produced by powder bed fusion require machining of supports, polishing, heat treatment, and sterilisation before clinical application.
[146]	Ti-6Al-2Sn-4Zr-2Mo-Si near-α Ti-alloy	LPBF + 2× and 3× β-annealing HT	As-built martensite with poor ductility/Triplex and high-temperature duplex heat treatments decomposed the martensitic microstructure, increasing elongation to 16.0–16.5% while retaining ~1100–1155 MPa UTS; β-annealing gave the best creep resistance.
[147]	Ti-35Nb-7Zr-5Ta β-type Ti-alloy	LPBF	Strength–ductility trade-off in β-Ti/Without external post-processing, LPBF defect engineering introduced high dislocation density and nanoscale twins, delivering 816 MPa yield strength with 16.5% elongation in the as-fabricated condition.
[148]	Grade II pure Ti	LPBF + HIP @ 730 °C or 950 °C	Toughness anisotropy after HIP treatment/Sub-transus HIP at 730 °C gave the highest fracture toughness in the X-Z orientation, whereas 950 °C HIP reduced porosity but promoted grain coarsening and cleavage.
[149]	Ti-5553 + Ti-42Nb	LPBF	Post-recycling oxygen pickup limits reuse, unmelted Ti-42Nb particles impair strength/The as-built hybrid alloy achieved 725 MPa tensile strength with 24% ductility; the authors further identify ageing heat treatment as a promising route for additional strengthening.
[150]	Ti-24Nb-4Zr-8Sn metastable β-type	L-PBF + ST with air cooling/water quenching/ageing /furnace cooling	As-built β/ω microstructure limits strength/HT induced β → α'/α transformation; the strongest condition, solution treatment plus furnace cooling, increased UTS from 700 ± 6 MPa to 931 ± 7 MPa.
	Ti-35Nb β-type	L-PBF + HT @ 1000 °C for 24 h	Unmelted Nb and microstructural inhomogeneity/Heat treatment markedly improved microstructural homogeneity in the mixed-powder build, although unmelted Nb particles remained because Nb diffusion in Ti was still insufficient.
	Ti-13Nb-13Zr β-type	L-PBF + HT @ 800 °C + HT @ 500 °C, or HT @ 900 °C + quenching, or HT @ 660 °C + quenching	Corrosion optimisation after heat treatment/The review indicates that post-heat-treated Ti-13Nb-13Zr generally exhibited lower corrosion current densities than the as-built alloy, suggesting improved electrochemical stability after thermal treatment.
[118]	Ti-6Al-4V	LPBF + annealing HT	α' martensite and limited ductility/HT decomposed acicular α' martensite into lamellar α + β, improved elongation and fatigue behaviour, and the review identifies 800–850 °C HT as particularly beneficial.
	Ti-5Al-2Sn-2Zr-4Mo-4Cr	LPBF + HT	Ultra-fine lamellae constrain plasticity/Heat treatment thickened α lamellae, reduced dislocation density, rounded lamellar tips, and thereby improved plasticity whilst retaining the very high strength characteristic of LPBF Ti-5Al-2Sn-2Zr-4Mo-4Cr.

Caption: GAP—graded alloy processing.

3.3.1. Electron Beam Melting (EBM)

EBM has emerged as a well-established additive manufacturing route for Ti-alloy components, particularly due to its suitability for producing complex geometries under elevated build temperatures, which can help mitigate residual stresses; nevertheless, its broader industrial adoption still depends on addressing challenges related to surface finish, dimensional accuracy, microstructural control and post-processing requirements.

Table 12 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of EBM as a manufacturing route for Ti-alloy components. EBM benefits from elevated build temperatures that can reduce residual stresses, but surface roughness, porosity, and microstructural control continue to require post-processing.

Table 12. Representative studies on Ti-alloy materials manufactured by EBM, a sub-technique of PBF.

Ref	Material	Technique	Challenges/Highlights
[151]	Ti-6Al-4V	EBM + grinding	Rough surface and low elongation/Despite its rougher as-built surface, EBM Ti-6Al-4V ELI showed higher hardness than cast and wrought material and comparable grindability, indicating good suitability for dental-component manufacture.
[152]	Ti-6Al-4V	EBM + alkali–acid–heat (AlAcH) chemical surface treatment	No visible apatite after treatment/AlAcH generated 200–300 nm nano-topographical features and a titania-rich surface; the 10M, 24 h condition gave the greatest Ca and P deposition after simulated body fluid (SBF) immersion.
[153]	Ti–45Al–7Nb–0.3W	EBM + in-process intermediate reheating + HIP	Pore-free densification remains challenging/Higher preheating and intermediate reheating acted as an in-situ thermal treatment, suppressing micro-/macro-cracking and enabling a fine full lamellar microstructure with 2750 MPa compressive strength and 37% strain-to-fracture; HIP was proposed to remove residual pores.
[154]	Ti-6Al-4V	EBM + modified local Preheat2 sintering	Semi-sintered powder removal and brittleness/Localised Preheat2 sintering made residual powder easier to remove and improved build efficiency by 14–37% with comparable tensile strength, although oxygen pickup in reused powder reduced elongation.
[155]	Ti-48Al-2Cr-2Nb γ -type	EBM + machining + HIP	Porosity, keyhole defects, Al loss/Medium energy input gave the best strength–microstructure balance; the study further notes that machining should remove the Fe-contaminated interface, while HIP could close residual pores.
[156]	Ti-6Al-4V	EBM + HIP @ 920 °C for 2 h	Porosity-driven fatigue crack initiation/HIP eliminated pores and increased the fatigue limit to 580 MPa despite lower tensile strength, whereas HT alone coarsened the microstructure without improving fatigue behaviour.
[157]	Ti-48Al-2Nb-2Cr	EBM + HIP or HT + machining	Machinability, porosity, and surface-finish control/HIP plus subsequent HT transformed the near- γ structure into a fully lamellar microstructure, reduced microporosity, increased hardness, and roughly doubled tool life during dry turning.
[158]	Ti-6Al-4V	EBM + HIP + machining	Porosity and anisotropy control/HIP-consolidated powder achieved >99.9% density, improved yield strength and UTS relative to standard EBM, and produced a more isotropic, equiaxed microstructure with graded-property capability.
[159]	Ti-43.5Al-4Nb-1Mo-0.1B γ -Ti-aluminide	EBM + HIP	HIP densification versus microstructural coarsening/For EBM-built TNM-B1, hot working was identified as a promising alternative to HIP, producing a dense and refined microstructure, whereas HIP removed porosity but significantly coarsened the microstructure.
[160]	Ti-43.5Al-4Nb-1Mo-0.1B	EBM	Gas porosity and brittle β_0 -phase/Optimised EBM yielded 99.9% relative density; the paper notes that subsequent HIP could almost eliminate residual gas porosity, whilst future heat treatment is required to tailor the brittle β_0 -containing microstructure.
[161]	Ti-24Nb-4Zr-8Sn metastable β -Ti-alloy	EBM	Thermal-history-induced microstructural gradients/The study treats post-processing principally as natural cooling after build completion; thermal-history analysis showed microstructural gradients in β/α distribution, highlighting the need for subsequent control strategies.
[159]	Ti-43.5Al-4Nb-1Mo-0.1B	EBM + HIP	Porosity closure without grain coarsening/Hot working was identified as a promising alternative to HIP, achieving void reduction whilst retaining a finer, denser, and more refined microstructure than HIP-treated material.
[162]	Ti-6Al-4V	EBM + surface coating post-processing	High SR and particle agglomeration/For EBM Ti-6Al-4V, the review highlights rougher as-built surfaces and larger particle aggregates; polymer/HA coating reduced SR and enhanced mesenchymal-cell adhesion and proliferation.
[38]	Ti-6Al-4V; Ti6242	EBM, followed by post-HT and/or HIP	Residual stress and internal porosity/For EBM Ti-alloy components, post-processing is described as reducing residual stress and porosity; HIP further improves microstructural homogeneity and ductility by closing defects and pores.
[163]	Ti-6Al-4V	EBM + HT	Coarser α lamellae, lower strength/For EBM-built Ti-6Al-4V, preheating promoted $\alpha + \beta$ formation and stress relief; HT caused less coarsening than in SLM, and post-processed data converged closely.
[164]	Ti-48Al-2Cr-2Nb γ -Ti-aluminide	EBM + HT @ 1473K for 2 h with Ar + machining	Severe-condition roughness and edge cracking/Heat treatment altered phase constitution and hardness response; under moderate machining conditions surface integrity remained acceptable, whereas the most severe condition (3C) promoted cracking, pull-out, and roughness deterioration.
[165]	Ti-6Al-4V	EBM + machining + HT + HIP	Rough surface and porosity control/The review indicates that post-machining is the most effective route for improving EBM surface finish, whilst HIP reduces porosity and enhances fatigue toughness in Ti-6Al-4V components.
[166]	Ti-6Al-4V	EBM + turning	Rough as-built surface, finishing energy/Post-process turning substantially improved surface finish, reducing $Ra_{ }$ to 1.51 μm and $Ra_{\perp}$ to 0.26 μm ; higher material-removal rates lowered machining energy, whereas lower speed and depth of cut gave the best roughness.
[167]	Ti–44.5Al–2V–1Nb–2Cr–0.1Gd β -solidifying γ -Ti-aluminide	EBM	Layerwise Al loss and microstructural inhomogeneity/The as-built SEBM material exhibited a lamellar $\gamma + \alpha_2 + \beta_0$ structure with alternating Al-rich/Al-depleted bands; the authors specifically recommend subsequent heat treatment to homogenise microstructure and properties.
[168]	Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-5Al-2.5Sn	EBM + HT + HIP + grinding + polishing + SPT, and machining	Surface irregularity and internal porosity/The review indicates that post-processing remains important after EBM to optimise microstructure, reduce internal defects, improve surface finish, and enhance service reliability.
[169]	Ti-6Al-4V	EBM + vacuum HT: stress-relief annealing (HT600), annealing (HT800), or solution treatment (HT920)	Pores and corrosion susceptibility/Annealing at 800 °C for 1h delivered the best post-processing outcome, increasing β -phase content, reducing grain-boundary density and pitting, and lowering corrosion current by 79.82%.

Table 12. Cont.

Ref	Material	Technique	Challenges/Highlights
[170]	Ti-44.5Al-2V-1Nb-2Cr-0.1Gd β -solidifying γ -Ti-aluminide	EBM + HIP + HT annealing (HT1) or HT thermal cycling (HT2)	Al loss, columnar grains, porosity/HIP nearly eliminated residual porosity, while HIP + HT1 fully fragmented columnar grains into a fine-grained structure and delivered the most balanced room- and high-temperature properties.
[171]	Ti-48Al-2Cr-2Nb	EBM + HIP	Limited ductility and fracture-mode discrimination/HIP-treated EBM Ti-48Al-2Cr-2Nb exhibited equiaxed and duplex microstructures; confocal roughness mapping reliably distinguished brittle propagation from final fracture zones across 650–760 °C testing.

Caption: SPT—Shot Peening Treatment.

3.3.2. Selective Laser Melting (SLM)

SLM has become one of the most extensively adopted AM routes for Ti-alloy components, principally owing to its capability to produce complex geometries with high dimensional accuracy and fine feature definition. Nevertheless, its wider industrial utilisation remains contingent upon the effective mitigation of residual stress, microstructural anisotropy, surface quality limitations and the continuing requirement for post-processing.

Table 13 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of SLM as a manufacturing route for Ti-alloy components. The reader here finds that SLM provides high geometric capability and fine feature definition, but post-processing remains necessary to address residual stress, anisotropy, and surface-quality limitations.

Table 13. Representative studies on Ti-alloy materials manufactured by SLM, a sub-technique of PBF.

Ref	Material	Technique	Challenges/Highlights
[172]	Grade IV pure Ti	SLM + chemical polishing in HF or HF/HNO ₃ solutions	Adhered powder and dimensional control/Optimised HF/HNO ₃ polishing removed partially melted particles, improved wettability, and brought pore dimensions closer to the CAD design, although excessive treatment reduced strut size and compressive strength.
[173]	Ti-5Al-2.5Sn α -type	SLM + HT @ 600–1100 °C for 2 h with furnace cooling	Columnar prior- β , Martensitic α' and poor ductility/Subtransus post-HT promoted recrystallisation and α' decomposition, markedly improving ductility; treatments in the 650–850 °C range enabled tensile properties exceeding conventionally processed Ti-5Al-2.5Sn.
[174]	Grade I pure Ti	SLM + HT @ 650 or 850 °C for 1 h	Weak isotropy in as-built state/Heat treatment at 650 °C for 1 h induced recrystallisation to an equiaxed, weak-textured microstructure and markedly reduced tensile anisotropy without prior plastic deformation.
[175]	Ti-6Al-4V	SLM + HT @ 800 °C for 2 h and/or HIP	Residual porosity and directional fatigue/Stress-relief treatment improved ductility but reduced strength, whereas HIP eliminated detectable porosity and provided the most favourable strength–ductility balance together with markedly improved fatigue stability.
[176]	TiB-reinforced Ti-6Al-4V MMC	SLM + HT @ 1050 °C for 2 h	Low ductility and lamellar microstructure/Post-HT transformed the matrix into fine near-equiaxed α -Ti with homogeneously dispersed TiB whiskers, increasing fracture strain from 19.3% to 43.6% whilst retaining 1428 MPa compressive strength.
[177]	Ti-6Al-4V	SLM + HT	Balancing ductility, strength and roughness/Barrel finishing reduced surface roughness to about 0.5 μ m and increased elongation by ~25%, whilst industrial heat treatments improved elongation by >30% with only moderate strength reduction.
[162]	Ti-6Al-4V	SLM + sandblasting, vibratory finishing, chemical polishing, HT, laser polishing, and thermochemical modification.	Adhered particles and surface defects/For LPBF/SLM Ti-6Al-4V, post-processing is extensively used to remove or attenuate unmelted particles, reduce roughness and defects, and improve fatigue and biological performance.
[105]	Ti-6Al-4V	SLM for medical implants	Support removal and surface finishing/The review indicates that Ti-6Al-4V/Ti64 implants produced by SLM require machining of supports, polishing, HT, and sterilisation prior to clinical application.
[178]	Ti-6Al-2Sn-4Zr-2Mo near- α Ti-alloy	SLM + isothermal annealing @ 650–1025 °C, water quenching, and standard ageing at 595 °C	Ageing-induced embrittlement after martensite decomposition/Post-HT clarified the temperature-dependent decomposition of SLM martensite, but the water-quench-plus-ageing route severely embrittled Ti-6242 through β reduction and Ti ₃ Al precipitation.
[179]	Ti-6Al-2Zr-1Mo-1V, near- α Ti-alloy	SLM + vacuum HT @ 800 °C for 1 h or 4 h	α' martensite and limited ductility/Heat treatment converted acicular α' martensite into a basket-weave α + β structure, markedly improving ductility and fracture toughness, although tensile and yield strengths decreased.
[180]	Ti-6Al-4V	SLM + VPFP + annealing @ 700–850 °C for 4 h with furnace cooling	Acicular α' martensite limits ductility/HT transformed acicular α' martensite into α -dominant microstructures, reduced strength and hardness, and increased elongation by over 200%, reaching a maximum of 13%.

Table 13. Cont.

Ref	Material	Technique	Challenges/Highlights
[181]	Grade II pure Ti	SLM + HT	High oxygen, brittle as-built martensite/650 °C/1 h ht produced a favourable recrystallised-plus-martensitic microstructure, reducing strength slightly but increasing elongation to 9.5% while retaining 924 MPa tensile strength.
[38]	Ti-6Al-4V (Ti64), TA15, Ti64–25Ti–0.5O, Ti64–(4.5%)316L	SLM + HT and/or HIP	Residual stress, martensite, porosity/For SLM Ti-alloys, post-HT decomposes α' martensite and relieves residual stress, whilst HIP further reduces porosity and generally improves ductility and structural integrity.
[163]	Ti-6Al-4V	SLM + HT	Martensitic α' and HT softening/For SLM-built Ti-6Al-4V, HT generally coarsened the α/α' width and reduced yield strength, although it also diminished method-dependent discrepancies in microstructure and strength.
[182]	Ti6Al4V–x wt.% TiB ₂ Ti-MMC	SLM + solution–ageing @ 950 °C for 1 h + water quench; 580 °C for 6 h, air cooling	TiB coarsening versus ductility gains/Solution–ageing transformed α' martensite into an $\alpha + \beta$ basket-weave structure and improved quasi-static ductility; the 0.01 wt.% TiB ₂ composite achieved 1957 MPa and 23.7% strain.
[183]	Ti–Nb–Zr–Ta β -type Ti-alloy	SLM + solid-solution HT	Homogeneity after in-situ alloying/The review indicates that post-SLM solid-solution heat treatment can deliver a high tensile-strength-to-elastic-modulus ratio, reaching about 56 GPa, despite residual Nb and Ta particles.
[184]	Ti–23.4Al–24.5Nb	SLM + HT @ 750–900 °C for 30 min in air and water quenching	Orthorhombic plate coarsening versus hardening/HT decomposed the metastable β -solid solution into lamellar Orthorhombic -phase; higher temperatures coarsened orthorhombic platelets, reduced dispersion hardening, and increased elastic modulus, with 900 °C recommended for a better strength–ductility balance.
[168]	Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-5Al-2.5Sn	SLM + HT + HIP + grinding + polishing + SPT, and machining	Porosity, residual stress, surface roughness/The review identifies post-processing as essential after SLM, primarily to reduce porosity, relieve residual stresses, refine surface condition, and improve durability in demanding applications.
[185]	Ti-6Al-4V	SLM + turning, milling, drilling, grinding, polishing, HT, and HIP	Anisotropy, TW, roughness control/The review concludes that combined post-processing markedly improves surface finish, dimensional accuracy, residual-stress state, and fatigue-related integrity, although anisotropic microstructure and elevated hardness still hinder machinability.
[186]	Ti-6Al-4V	SLM + annealing @ 850 °C for 2 h and dry post-milling	Thin-wall chatter and TW/Dry post-milling of annealed SLM Ti-6Al-4V thin walls achieved aeronautical-grade Ra ($\sim 1.26 \mu\text{m}$) when multilayer-coated tooling and trochoidal paths limited temperature rise and stabilised machining.
[187]	Ti-6Al-4V	SLM + WJM	Minimal roughness change after WJM/Pure water jet chiefly cleaned the surface and preserved substrate integrity, yet produced no meaningful reduction in Sa, Sq, or Sz after treatment.
		SLM + AWJM	Abrasive embedment and corrosion initiation/Quartz-sand abrasive water jet, especially at 30 MPa, removed adhered powder and surface defects most effectively, reducing Sa by up to 50% on rougher S5 specimens.
		SLM + WIJM	Crack widening under ice impact/Water–ice jet provided partial powder removal and modest reductions in Sz and Sv, but local surface damage and crack widening were also observed.
[188]	Custom Ti-mesh	SLM	Mesh exposure and clinical heterogeneity/SLM-customised meshes showed favourable bone-gain outcomes and generally predictable clinical performance, yet the evidence base remained limited by small cohorts, heterogeneous protocols, and complication-reporting variability.

Caption: AWJM—Abrasive Water Jet Machining, MMC—Metal Matrix Composite, VPFP—variable parameter forming process, WJM —Water Jet Machining, WIJM—Water-Ice Jet Machining.

3.3.3. Direct Metal Laser Sintering (DMLS)

DMLS has attained a significant position amongst additive manufacturing routes for Ti-alloy components, primarily by virtue of its capacity to manufacture geometrically intricate structures with high dimensional accuracy and relatively refined feature definition. Notwithstanding these advantages, its more widespread industrial adoption remains conditional upon the effective control of residual stress, microstructural heterogeneity, surface quality limitations and the continuing reliance on post-processing operations.

Table 14 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of DMLS as a manufacturing route for Ti-alloy components. Table 14 indicates that DMLS is well suited to complex Ti-alloy geometries, although heat treatment, HIP, shot peening, and surface finishing are often required to improve ductility, fatigue response, and surface integrity.

Table 14. Representative studies on Ti-alloy materials manufactured by DMLS, a sub-technique of PBF.

Ref	Material	Technique	Challenges/Highlights
[189]	Ti-6Al-4V	DMLS + SPT	Internal roughness-induced joint friction/Post-build shot peening was applied to improve surface finish; Ti-6Al-4V joints showed smoother motion than aluminium, yet the authors concluded that dedicated internal finishing remains necessary.
[190]	Ti-6Al-4V	DMLS + annealing @ 850 °C for 2 h in Ar	Hardness loss during stress relief/Stress-relief annealing homogenised the as-built martensitic/lamellar structure, dissolved the build-pattern spacing, stabilised hardness at 350–370 HV, and stabilised corrosion potential without markedly changing corrosion rate.
		DMLS + abrasive blasting @ 0.2–0.6 MPa	Roughness control versus surface morphology/Abrasive blasting reduced roughness as pressure increased; spherical Zirblast produced the most pronounced smoothing, whereas sharp-edged white corundum generated rougher, more notched surface morphologies.
[191]	TiN-reinforced Ti-6Al-4V MMC	DMLS	Porosity control and tribological improvement/Increasing TiN content and laser power improved hardness, reduced friction to 0.33–0.42, and promoted dense, well-bonded reinforcement dispersion with beneficial in-situ nitride/intermetallic phases.
[192]	Ti-6Al-4V	DMLS + annealing HT	Strength–ductility trade-off during HT/HT reduced tensile and yield strength, yet substantially increased elongation and ductility, reflecting microstructural evolution away from the as-built martensitic condition.
		DMLS + HIP	Roughness limits fatigue gains after HIP/HIP improved fatigue strength of as-built Ti-6Al-4V; however, the review indicates that fatigue remained constrained by the deleterious effect of surface roughness.
		DMLS + SPT	SPT produced only a slight increase in ultimate tensile strength, whilst fracture still initiated at pores and unmelted powder particles in DMLS material.
[193]	Ti-6Al-4V	DMLS + HT @ 650 °C for 3 h + machining	Powder-reuse contamination during sieving/HTed DMLS Ti-6Al-4V retained broadly stable tensile and high-cycle fatigue performance across reuse cycles, although late-run Fe/Cr/Ni contamination generated brittle precipitates.
[194]	Ti-6Al-4V	DMLS + HT @ 800 °C, for 1 h 30 min hold, 4 h cooling) + machining + selective polishing + ethylene oxide sterilisation	Fit precision and infection control/The post-processing route combined thermal stabilisation, precision re-machining and differential surface finishing, contributing to excellent clinical fit and satisfactory short-term survival, although poor fit could precipitate recurrent infection and failure.
[195]	Ti-6Al-4V	DMLS + HT @ 650 °C for 3 h, annealing @ 940 °C for 2 h + machining	Residual stress, inhomogeneity, Al loss/Rescanning reduced surface roughness by about 51% and improved alloy homogenisation; subsequent heat treatment transformed α' martensite into lamellar $\alpha + \beta$, enabling 99.9% density, 942.9 MPa strength and 17% ductility.
[196]	Ti-6Al-4V	DMLS + TIG welding + CNC machining, brushing/polishing, and cleaning	Geometric defect recovery without property loss/TIG reconditioning successfully restored a defective DMLS Ti-6Al-4V implant to medically acceptable geometry, with deviations below 1 mm and functional properties considered comparable to the original part.
[197]	Ti-6Al-4V	DMLS + laser cavitation	Surface roughness-driven fatigue crack initiation/Laser cavitation melted unmelted particles, reduced roughness, introduced compressive residual stress, increased hardness, and extended torsional fatigue life from 19,791 to 36,288 cycles.
[198]	Ti-6Al-4V	DMLS	Poor tribology in biofluids/DMLS Ti-6Al-4V exhibited 23% lower friction and 68% lower wear than cast alloy, chiefly attributed to higher hardness and greater hydrophilicity under biofluid lubrication.
[199]	Medical grade Ti-alloy not specified	DMLS + polishing and/or veneering	Layered surface requires additional finishing/The review indicates that DMLS provides design flexibility and clinically acceptable framework precision, but layered manufacture commonly necessitates post-processing to obtain smoother surfaces and improved aesthetic outcomes
[168]	Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-5Al-2.5Sn	DMLS + HT + HIP + grinding + polishing + SPT, and machining	Incomplete densification and surface defects/For SLS-based Ti manufacture, the review frames post-processing as necessary to improve densification, mitigate defects, enhance surface quality, and support acceptable functional performance.
[200]	Ti-6Al-4V	DMLS + grinding/polishing + SPT @ 0.3 and 0.4 MPa for 120 s	Roughness increase versus corrosion stability and higher peening pressure worsens corrosion/Pre-polished DMLS Ti-6Al-4V showed grain refinement and hardness improvement after 0.3 MPa shot peening, but corrosion resistance remained inferior to the untreated DMLS reference surface, and the 0.4 MPa treatment further increased hardness and refined crystallites, yet greater surface development and embedded CrNi shot residues yielded the poorest corrosion response.
[188]	Medical grade Ti-alloy/Ti-mesh not specified	DMLS	Mesh exposure during healing phase/Across the DMLS studies, customised Ti-meshes enabled clinically useful vertical and horizontal bone gain with successful planned implant placement, although exposure-related complications remained the principal limitation.

3.4. Other Methods

Section 3.4 also includes less conventional AM routes, represented here by a single study on Cold Spray Additive Manufacturing (CSAM) of Ti-6Al-4V. Although distinct from fusion-based processes, this work remains highly relevant, as it demonstrates how targeted post-processing can compensate for deposition-induced porosity and weak inter-particle cohesion. Jin et al. [38] conducted a Cold Spray Additive Manufacturing (CSAM) on Ti-6Al-4V, followed by post-HT, HIP, and SPT. Challenges arose due to high porosity after deposition and weak bonding. For CSAMed Ti-6Al-4V, post-processing is reported to improve inter-particle adhesion, reduce porosity, relieve defects, and enhance tensile strength, ductility, and microhardness.

4. Integrated Ti-Alloy Manufacturing Quality Framework

The literature reviewed throughout this study demonstrates that the performance of additively manufactured Ti-alloy components is governed by a complex chain of interrelated phenomena extending from process parameters to final component reliability. Although numerous studies investigate individual stages of this chain, a holistic perspective is often lacking. To address this gap, an Integrated Ti-Alloy Manufacturing Quality Framework (ITMQF) is proposed, as illustrated in Figure 9.

The framework highlights the causal relationships linking additive manufacturing process parameters, thermal history, microstructural evolution, defect formation, residual-stress development, post-processing operations, surface integrity, and final functional performance. Process-specific parameters associated with SLM, EBM, WAAM, and DED directly influence heat transfer conditions and solidification behaviour, which subsequently determine grain morphology, phase composition, texture development, and anisotropic characteristics.

These microstructural features govern the formation of defects such as porosity, lack-of-fusion regions, cracking, and surface irregularities. Defect populations, together with thermal gradients generated during manufacturing, contribute to residual-stress accumulation and dimensional instability. Consequently, post-processing operations including hot isostatic pressing, heat treatment, machining, and surface-finishing techniques become essential for mitigating manufacturing-induced limitations.

The framework further identifies surface integrity as the critical link between manufacturing processes and functional performance. Surface roughness, residual stresses, subsurface deformation, and metallurgical alterations directly influence fatigue resistance, wear behaviour, corrosion performance, and structural reliability. Ultimately, component reliability emerges as the cumulative result of all preceding stages rather than the consequence of a single manufacturing operation.

The proposed framework provides a unified perspective for understanding the interactions between additive manufacturing, hybrid manufacturing, and post-processing technologies. Furthermore, it highlights the necessity of integrated process optimisation strategies capable of simultaneously controlling microstructure, defects, surface integrity, and functional performance in advanced Ti-alloy components.

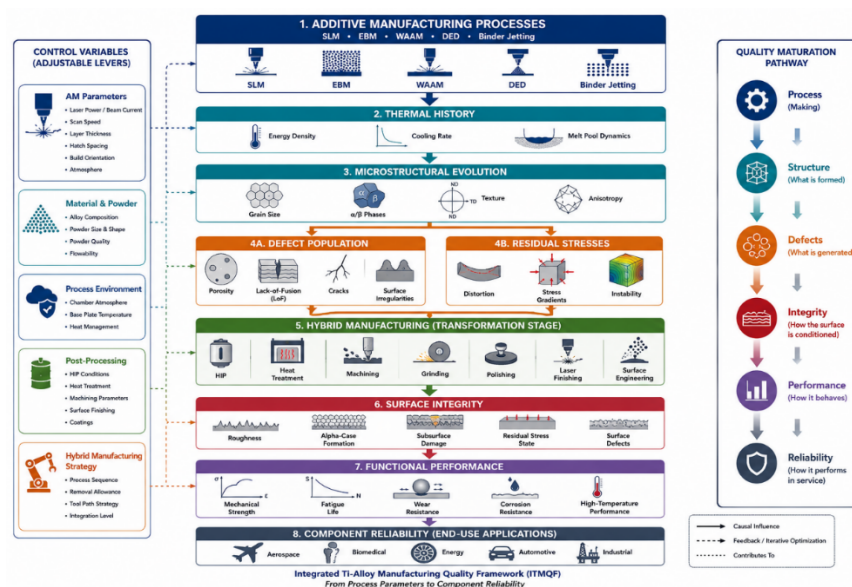


Figure 9. Integrated Ti-Alloy Manufacturing Quality Framework (ITMQF) illustrating the causal relationships between additive manufacturing parameters, microstructural evolution, defect formation, post-processing operations, surface integrity, functional performance, and component reliability.

5. Surface Integrity as the Critical Link Between Manufacturing and Functional Performance

Surface integrity represents one of the most influential factors governing the functional performance and long-term reliability of Ti-alloy components. While additive manufacturing, hybrid manufacturing, and post-processing technologies are frequently evaluated in terms of dimensional accuracy, productivity, and microstructural characteristics, the final performance of a component is often dictated by the condition of its surface and subsurface layers. Consequently, surface integrity should be regarded as the critical link connecting manufacturing processes to in-service behaviour.

Surface integrity encompasses a combination of geometrical, mechanical, metallurgical, and physical characteristics generated during manufacturing and post-processing operations. These include surface roughness, residual stress distributions, subsurface deformation, microstructural alterations, surface defects, and chemically modified layers. Unlike bulk material properties, which are generally governed by alloy composition and thermal history, surface integrity is strongly influenced by process-specific conditions and can vary significantly between manufacturing routes.

In additively manufactured Ti-alloy components, surface roughness remains one of the most persistent challenges. Powder adhesion, partially melted particles, stair-stepping effects, and melt-pool instabilities frequently generate irregular surface topographies that act as preferential sites for stress concentration and crack initiation. Such features become particularly critical in fatigue-loaded components, where failure often originates from surface imperfections rather than internal defects.

Residual stresses constitute another major component of surface integrity. The steep thermal gradients associated with additive manufacturing processes such as SLM and DED promote the accumulation of tensile residual stresses, which may contribute to distortion, dimensional instability, and premature crack initiation. Although post-processing operations including heat treatment and hot isostatic pressing can reduce residual-stress levels, subsequent machining and finishing operations may introduce new stress states within the surface layer. Therefore, surface integrity should be evaluated as the cumulative result of the entire manufacturing chain rather than a single processing stage.

Metallurgical modifications occurring near the surface further influence component performance. In Ti-alloys, exposure to elevated temperatures may lead to the formation of oxygen-enriched layers commonly referred to as alpha-case. This brittle layer reduces ductility and fatigue resistance and is therefore considered detrimental in aerospace and biomedical applications. In addition, machining-induced plastic deformation and microstructural refinement may alter local hardness, wear resistance, and crack-propagation behaviour.

The interaction between roughness, residual stresses, microstructural alterations, and defect populations ultimately determines fatigue performance. Numerous studies have demonstrated that fatigue life is governed not only by internal porosity but also by the combined effects of surface condition and subsurface damage. Consequently, improvements in fatigue resistance frequently require integrated strategies involving process optimisation, heat treatment, machining, polishing, shot peening, laser finishing, or other surface-engineering techniques.

From a hybrid manufacturing perspective, surface integrity represents the primary mechanism through which post-processing operations enhance component quality. Processes such as machining, grinding, polishing, laser finishing, and surface engineering do not merely improve surface appearance; they actively modify the mechanical and metallurgical state of the surface layer, thereby influencing fatigue behaviour, wear resistance, corrosion performance, and overall reliability.

Therefore, surface integrity should be considered a key performance indicator for advanced Ti-alloy manufacturing systems. Future developments in additive and hybrid manufacturing should increasingly focus on integrated strategies capable of simultaneously controlling microstructure, residual stresses, surface condition, and defect populations. Such an approach is essential for achieving the reliability levels required in fatigue-critical aerospace, biomedical, and energy applications.

6. Defect Taxonomy and Failure Mechanisms in Ti-Alloy Manufacturing

The manufacturing of Ti-alloy components involves a wide range of process-induced imperfections that may significantly influence dimensional accuracy, mechanical performance, fatigue resistance, and long-term reliability. Although individual defects are frequently discussed within the context of specific manufacturing technologies, a unified classification system remains largely absent from literature. To address this gap, Figure 10 proposes a defect taxonomy for Ti-alloy manufacturing systems, integrating defects originating from additive manufacturing, hybrid manufacturing, machining, heat treatment, and surface-engineering operations. The proposed taxonomy categorizes defects into five principal groups: volumetric, geometrical, surface, metallurgical,

and mechanical defects. This classification provides a structured framework for understanding the origin of manufacturing-induced imperfections and their potential consequences for component performance.

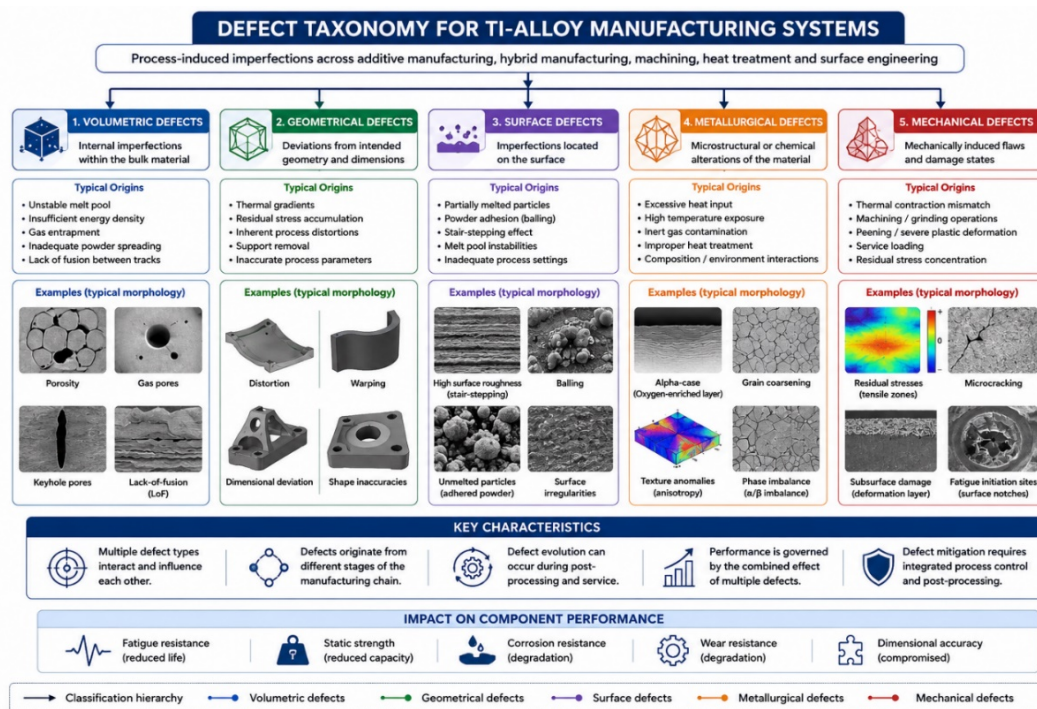


Figure 10. Integrated defect taxonomy for Ti-alloy manufacturing systems, showing the classification, origins, and interactions of volumetric, geometrical, surface, metallurgical, and mechanical defects generated throughout the manufacturing chain. The framework highlights how defect populations collectively influence surface integrity, fatigue behaviour, and long-term component reliability.

Volumetric defects are primarily associated with additive manufacturing processes and include porosity, gas entrapment, keyhole formation, and lack-of-fusion regions. These defects are typically generated by unstable melt-pool behaviour, insufficient energy density, inadequate powder spreading, or process-parameter variations. Because they are located within the material volume, such defects frequently act as stress concentrators and fatigue crack initiation sites.

Geometrical defects comprise dimensional deviations, distortion, warping, and shape inaccuracies. These imperfections are largely related to thermal gradients and residual-stress accumulation during manufacturing. Although geometrical defects may not directly reduce material strength, they often compromise assembly accuracy and may necessitate extensive post-processing operations.

Surface defects constitute one of the most critical categories in fatigue-sensitive applications. Roughness, balling phenomena, partially melted particles, and surface irregularities are particularly common in additively manufactured components. These features increase local stress concentrations and significantly accelerate fatigue crack initiation under cyclic loading conditions.

Metallurgical defects arise from undesirable microstructural transformations and chemical alterations. Examples include alpha-case formation, excessive grain growth, texture-related anisotropy, and phase imbalances. Such defects may reduce ductility, alter hardness distributions, and negatively affect fatigue and fracture behaviour.

Mechanical defects encompass residual stresses, subsurface damage, microcracking, and fatigue initiation sites generated during manufacturing or post-processing operations. Unlike volumetric or metallurgical defects, these imperfections often evolve throughout the service life of the component and therefore play a critical role in structural reliability.

An important observation emerging from the literature is that defect categories rarely occur independently. Instead, strong interactions frequently exist between volumetric defects, residual stresses, surface condition, and microstructural features. Consequently, component performance is typically governed by the combined effect of multiple defect populations rather than by a single dominant imperfection.

The proposed taxonomy therefore provides a holistic perspective for analysing defect formation mechanisms across the entire manufacturing chain. Furthermore, it highlights the necessity of integrated process-control and

post-processing strategies aimed at simultaneously minimizing defect populations and improving overall component reliability.

7. Hybrid Manufacturing as a Critical Transition from Near-Net Shape to Functional Reliability

Hybrid manufacturing should not be interpreted merely as the physical combination of additive and subtractive operations within the same production platform. In the context of Ti-alloys, it represents a critical technological transition between geometric freedom and functional reliability. Additive manufacturing enables the production of complex near-net-shape components with high material efficiency, internal features, lightweight architectures, and topology-optimised geometries. However, the as-built condition rarely satisfies the dimensional, surface-integrity, residual-stress, and fatigue-performance requirements demanded by aerospace, biomedical, energy, and high-performance industrial applications.

This limitation is particularly relevant for Ti-alloys because their low thermal conductivity, strong chemical reactivity, high strength at elevated temperature, and poor machinability make post-processing more difficult than for many other engineering alloys. As a result, additive manufacturing alone cannot generally ensure the simultaneous achievement of geometric complexity, tight tolerances, controlled residual stresses, acceptable surface roughness, and fatigue-critical reliability. Hybrid manufacturing emerges precisely to close this gap.

From a process-chain perspective, additive manufacturing provides geometry generation, while subtractive and finishing operations provide dimensional correction, surface conditioning, and functional tuning. Machining, grinding, polishing, laser finishing, hot isostatic pressing, and heat treatment should therefore be understood not as secondary corrective steps, but as integral elements of a quality-maturation pathway. This pathway transforms a geometrically valid Ti-alloy preform into a component capable of satisfying service requirements.

The scientific value of hybrid manufacturing lies in its ability to control the interaction between process-induced defects and performance-limiting surface conditions. For example, additive manufacturing may introduce porosity, lack-of-fusion defects, high surface roughness, anisotropic microstructures, and tensile residual stresses. Subsequent machining or finishing operations can reduce surface roughness and remove partially melted particles, but may also introduce subsurface deformation, tensile residual stresses, or thermal damage if poorly controlled. Similarly, heat treatment and hot isostatic pressing may reduce residual stresses and internal porosity, but cannot fully compensate for surface-related fatigue initiation if the external topography remains inadequate.

Therefore, hybrid manufacturing should be evaluated as an integrated optimisation problem rather than as a simple sequential combination of independent operations. The sequence, intensity, and interaction of additive, thermal, mechanical, and surface-engineering stages determine the final balance between dimensional accuracy, surface integrity, microstructural stability, defect mitigation, and mechanical performance. In this sense, the effectiveness of hybrid manufacturing depends not only on the individual performance of each process, but on the compatibility between consecutive stages.

A major unresolved challenge concerns the propagation of defects and residual stresses across the manufacturing chain. Residual stresses generated during additive manufacturing may influence part distortion during machining, while machining-induced surface stresses may affect fatigue behaviour even after dimensional accuracy has been achieved. Likewise, internal defects that survive hot isostatic pressing or heat treatment may interact with surface notches introduced during finishing, creating combined failure mechanisms. These interactions demonstrate why hybrid manufacturing must be approached through a process–structure–integrity–performance perspective.

The most advanced hybrid strategies for Ti-alloys should therefore move beyond the simple integration of additive and subtractive equipment. Future hybrid platforms should incorporate in-situ monitoring, adaptive process planning, residual-stress prediction, tool-wear compensation, surface-integrity assessment, and closed-loop control. Such developments would allow manufacturing systems to adjust deposition, machining, and finishing parameters according to the evolving state of the component.

Consequently, hybrid manufacturing can be considered the enabling bridge between additive manufacturability and industrial qualification. Its role is not only to improve dimensional accuracy or surface finish, but to convert Ti-alloy components from near-net-shape structures into reliable engineering parts. For fatigue-critical and safety-critical applications, this distinction is fundamental. The success of hybrid manufacturing will ultimately depend on its capacity to control the entire quality chain: geometry, microstructure, defects, residual stresses, surface integrity, and functional performance.

8. Discussion

The present review shows that research on Ti-alloy additive and hybrid manufacturing has shifted decisively from process demonstration towards the more demanding question of how manufacturing routes, post-processing strategies, surface integrity, and digital control collectively govern final component performance. This interpretation is supported by the review methodology, which explicitly targeted post-processing, residual stress, surface roughness, heat treatment, hot isostatic pressing, machining, and related performance indicators, as well as by the publication trend identified across the 2010–2025 period. The recent literature is no longer primarily concerned with demonstrating that Ti-alloys can be produced by additive manufacturing, but rather with determining how as-built limitations can be mitigated in order to achieve industrially credible and functionally reliable components.

A first important observation is the clear prominence of powder bed fusion (PBF) routes, particularly selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM), within the recent literature, as illustrated in Table 15. This predominance is technically understandable, since these processes are especially attractive for high-value Ti-alloy components requiring geometric complexity, controlled feature resolution, and comparatively good nominal accuracy. However, the same body of literature repeatedly shows that these advantages are accompanied by persistent metallurgical and surface-related limitations, including martensitic microstructures, residual stresses, porosity, support-removal requirements, and insufficient surface finish. Consequently, post-processing operations such as heat treatment and hot isostatic pressing (HIP) should not be interpreted as secondary refinements, but as central stages within the manufacturing chain. Heat treatment is widely used to decompose α' martensite and reduce residual stresses, whereas HIP is frequently associated with pore closure, improved structural integrity, and enhanced ductility. In parallel, machining, polishing, and sterilisation become indispensable whenever biomedical, fatigue-critical, or precision applications are involved.

Table 15 shows that recent literature is dominated by PBF-related routes, particularly SLM, DMLS, and EBM, while WAAM has also gained increasing attention because of its productivity and hybrid-manufacturing potential. This is technically understandable, since these processes are especially attractive for high-value Ti-alloy parts requiring geometric complexity and relatively good nominal accuracy. However, the same studies repeatedly show that these advantages are offset by persistent metallurgical and surface-related penalties, notably martensitic microstructures, residual stress, porosity, support-removal requirements, and inadequate surface finish. The representative studies summarised in Section 3 indicate that post-heat treatment and HIP are not secondary refinements, but central corrective operations: heat treatment is used to decompose α' martensite and relieve residual stresses, whilst HIP is repeatedly associated with pore closure, improved structural integrity, and better ductility. In parallel, machining, polishing, and sterilisation appear as indispensable downstream stages whenever biomedical, or precision applications are involved.

Table 15. Heat-map representation of the annual distribution of publications across the additive-manufacturing techniques addressed in Section 3.

Process	'11	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25
BJ						2	1	2	1	1	1	2	1
DED					1				1	2	1	1	2
WAAM							1	3	3	6	2	2	2
PBF								2	4	4	1		1
EBM	1		2	2	2		1	1	3		6	3	1
SLM				1	1		1	3	4	2	2	4	4
DMLS		1		1		1			1	4	1	3	2
CSAM											1		

A second trend concerns directed energy deposition (DED)-based routes, including wire arc additive manufacturing (WAAM), where the literature places greater emphasis on productivity, larger build envelopes, repair capability, and hybrid integration. WAAM is particularly attractive for expensive Ti-alloys, since near-net-shape deposition can reduce material waste and improve buy-to-fly ratios. Nevertheless, the process–property balance remains less favourable in terms of dimensional precision, surface quality, and local thermal control. The reviewed studies consistently indicate that post-deposition heat treatment, inter-layer conditioning, machining, and finishing operations are required to obtain acceptable mechanical response and geometrical stability. In this sense, DED technologies strongly reinforce the argument for hybrid manufacturing: the deposited state may be structurally useful, but it is often geometrically and metallurgically incomplete without subsequent corrective and maturation stages.

Binder jetting (BJ) occupies a distinct position within the reviewed literature. Compared with PBF and DED, the number of studies remains more limited, and the reported challenges are more strongly dominated by densification and dimensional-control issues. The BJ studies are consistently centred on curing, debinding, sintering, HIP, and surface finishing, with recurrent attention given to shrinkage, fragile green parts, anisotropic densification, residual porosity, and insufficient final fit. This suggests that, for Ti-alloys, BJ remains a highly post-processing-intensive route whose industrial viability depends less on the build step alone than on the success of the subsequent thermal, densification, and finishing chain. The process is therefore promising, particularly for specific near-net-shape or porous applications, but it is not yet as mature as PBF for structurally demanding Ti components.

Across all major process families, a common pattern emerges: irrespective of whether the initial route is BJ, PBF, DED, WAAM, or a hybrid configuration, the dominant technical bottlenecks remain porosity, residual stress, dimensional deviation, poor surface integrity, and microstructural heterogeneity. These limitations rarely occur independently. Instead, they often interact, producing complex defect populations and coupled failure mechanisms that cannot be adequately understood through single-defect analyses. For example, surface roughness may accelerate fatigue crack initiation, residual stresses may amplify crack propagation, and porosity or lack-of-fusion defects may reduce both static strength and fatigue resistance. This convergence supports the central premise of the review: post-processing is not an auxiliary or merely corrective stage, but an integral component of Ti-alloy manufacturing strategy.

The proposed Integrated Ti-Alloy Manufacturing Quality Framework (ITMQF) captures this transition by linking process parameters, thermal history, microstructural evolution, defect formation, surface integrity, and functional performance within a continuous cause-and-effect chain. Under this framework, additive manufacturing, hybrid manufacturing, post-processing, surface engineering, metrology, and digital manufacturing are not isolated technological domains, but interconnected elements of a broader quality-generation ecosystem. This perspective is particularly important for Ti-alloys because final component reliability depends simultaneously on bulk microstructure, defect population, residual-stress state, dimensional accuracy, surface condition, and application-specific performance requirements.

Among these factors, surface integrity emerges as one of the most decisive links between manufacturing route and service behaviour. Although considerable research has focused on bulk microstructural optimisation and defect reduction, the reviewed literature indicates that surface roughness, alpha-case formation, machining-induced deformation, residual stress redistribution, and near-surface damage frequently govern fatigue crack initiation, wear behaviour, corrosion response, and structural reliability. This observation helps explain why components with comparable bulk microstructures may display substantially different fatigue performance depending on their surface condition. Future optimisation strategies should therefore treat surface integrity as a primary design and qualification variable, rather than as a secondary quality indicator assessed only after manufacturing.

The analysis also clarifies the role of hybrid manufacturing. Traditionally, hybrid routes have often been described as additive manufacturing followed by subtractive correction. However, the evidence reviewed here suggests a more precise interpretation: hybrid manufacturing should be regarded as a quality-maturation strategy. Its purpose is not merely to correct dimensional error, but to transform the geometry, microstructure, defect population, residual-stress state, and surface condition of a near-net-shape component into a state compatible with functional requirements. This shifts the discussion from simple process integration to quality integration, which is particularly relevant for fatigue-critical aerospace, biomedical, and high-performance engineering applications.

A further implication concerns the transition towards data-driven manufacturing environments. Current quality-assurance strategies remain heavily dependent on post-process inspection, which identifies defects only after they have been generated. Emerging developments in in-situ monitoring, process sensing, machine learning, digital twins, and predictive modelling create opportunities to move from defect detection towards defect prediction and prevention. Such approaches could enable the real-time estimation of microstructural evolution, residual-stress accumulation, surface-integrity degradation, distortion, and performance limitations during production. This transition would substantially reduce uncertainty, improve process robustness, and support the broader qualification of Ti-alloy components manufactured through additive and hybrid routes.

Overall, the literature indicates that future progress in Ti-alloy manufacturing will not arise from the isolated optimisation of individual AM processes. Instead, it will depend on the coordinated control of feedstock characteristics, process parameters, thermal history, defect mitigation, post-processing, surface integrity, metrology, and performance validation within coherent manufacturing chains. The convergence of additive manufacturing, machining, heat treatment, inspection, artificial intelligence, and lifecycle assessment within unified digital ecosystems is therefore likely to define the next stage of development in the field. Achieving this level of integration remains a major scientific and industrial challenge, but it is also the most credible pathway towards reliable, high-performance, and digitally supported manufacturing systems for next-generation Ti-alloy components.

9. Future Research Roadmap for Advanced Ti-Alloy Manufacturing Systems

The evolution of Ti-alloy manufacturing is progressively shifting from isolated process optimisation towards fully integrated and intelligent manufacturing ecosystems. Although significant advances have been achieved in additive manufacturing, hybrid manufacturing, and post-processing technologies, several scientific and technological challenges remain unresolved. Future developments are expected to focus on the integration of manufacturing processes, material behaviour, surface integrity control, and digital intelligence within unified frameworks.

In the short term, research efforts will likely concentrate on improving process stability and defect mitigation. Particular attention should be directed towards the reduction of porosity, lack-of-fusion defects, residual stresses, and surface irregularities through enhanced process monitoring and parameter optimisation. Simultaneously, more sophisticated post-processing strategies capable of controlling microstructure and surface integrity in a predictable manner will be required.

The next stage of development is expected to involve the widespread adoption of hybrid manufacturing systems. Future hybrid platforms should integrate additive manufacturing, machining, heat treatment, surface finishing, and inspection technologies within a coordinated production environment. Such systems will enable dynamic process adaptation based on the evolving condition of the component, reducing the need for corrective operations and improving manufacturing efficiency.

A critical research direction concerns the transition from process control to quality prediction. Current manufacturing systems primarily rely on post-process inspection to verify component quality. Future approaches should increasingly employ predictive models capable of forecasting defect formation, residual-stress evolution, microstructural development, and surface-integrity degradation before these issues become critical. The integration of physics-based modelling with machine-learning algorithms is expected to play a central role in this transition.

Another major frontier is the development of Digital Twins for Ti-alloy manufacturing systems. Digital twins will enable the continuous virtual representation of components throughout the manufacturing lifecycle, allowing the prediction of process outcomes, performance degradation, and service behaviour. By integrating process parameters, sensor data, microstructural information, and performance models, digital twins may facilitate real-time optimisation and significantly improve manufacturing reliability.

Artificial intelligence is also expected to become a key enabler of next-generation manufacturing. AI-assisted process planning, adaptive parameter optimisation, predictive maintenance, tool-wear monitoring, and automated defect recognition have the potential to substantially enhance productivity and quality consistency. Furthermore, AI-driven decision-support systems may enable autonomous optimisation of complex hybrid manufacturing chains involving multiple interacting processes.

Beyond manufacturing itself, increasing attention should be devoted to sustainability and lifecycle performance. Future studies should evaluate not only manufacturing efficiency but also recyclability, energy consumption, material utilisation, repairability, and long-term reliability. Such considerations will become increasingly important as Ti-alloys are adopted in aerospace, biomedical, energy, and advanced transportation applications.

Ultimately, the future of Ti-alloy manufacturing is expected to converge towards intelligent, adaptive, and self-optimising production systems. The progression from additive manufacturing to hybrid manufacturing, digital twins, artificial intelligence, and autonomous manufacturing represents a natural technological evolution aimed at achieving simultaneous control of geometry, microstructure, defects, surface integrity, and functional performance. The successful integration of these technologies will define the next generation of high-performance Ti-alloy components and establish new standards for reliability in safety-critical applications.

Despite the remarkable progress achieved in additive manufacturing and hybrid manufacturing technologies for Ti-alloys, several critical challenges continue to limit their widespread adoption in safety-critical applications. Defect formation, residual-stress accumulation, surface-integrity degradation, process variability, and the lack of predictive quality-control strategies remain among the most significant barriers to achieving consistent and reliable component performance. At the same time, emerging developments in digital manufacturing, artificial intelligence, advanced sensing technologies, and integrated process control are creating new opportunities to transform the entire manufacturing paradigm.

The future of Ti-alloy manufacturing is therefore expected to evolve beyond isolated process optimisation towards intelligent and interconnected manufacturing ecosystems capable of simultaneously controlling geometry, microstructure, defect populations, surface integrity, and functional performance. This transition will require the integration of additive manufacturing, hybrid manufacturing, real-time monitoring, predictive modelling, digital twins, and AI-assisted decision-making within unified production frameworks.

Based on the trends identified throughout the reviewed literature, Figure 11 proposes a future research roadmap for advanced Ti-alloy manufacturing systems. The roadmap illustrates the expected technological

progression from conventional additive manufacturing towards autonomous manufacturing environments, highlighting the key enabling technologies, research priorities, and anticipated industrial impacts that are likely to shape the next generation of high-reliability Ti-alloy components.



Figure 11. Future research roadmap for Ti-alloy manufacturing systems, illustrating the technological progression from additive manufacturing towards hybrid manufacturing, predictive quality control, digital twins, artificial intelligence-assisted optimisation, and autonomous manufacturing ecosystems aimed at achieving zero-defect, high-reliability components.

10. Conclusions

This review has shown that the manufacture of Ti-alloys must be understood as an integrated process chain, rather than as a set of isolated manufacturing or post-processing operations. The final performance, reliability, and industrial viability of Ti components are governed by the interaction between manufacturing route, material response, defect formation, and post-processing strategy. Across the literature examined, additive and hybrid processes offer clear advantages in geometric freedom, material utilisation, and functional customisation, yet they also introduce persistent challenges linked to porosity, residual stress, dimensional deviation, surface integrity,

and microstructural heterogeneity. Consequently, post-processing emerges not as an auxiliary stage, but as a decisive stage within the overall process chain required to convert near-net-shape Ti-alloy parts into components with reliable engineering performance. Consequently, post-processing emerges not as an auxiliary stage, but as a decisive part of the overall manufacturing strategy for Ti-alloys.

- Ti-alloys remain strategically important engineering materials because they combine high specific strength, corrosion resistance, and biocompatibility, but their extraction, processing, and machining continue to impose significant economic and technical penalties.
- Among the manufacturing routes reviewed, powder bed fusion processes, especially SLM and DMLS, remain the most mature for complex Ti-alloy parts, although they require extensive corrective post-processing to address martensitic microstructures, residual stresses, and inadequate surface finish.
- DED-based routes, particularly WAAM, offer strong potential for large-scale and near-net-shape production, but their comparatively poorer dimensional accuracy and rougher surfaces make machining and thermal post-treatment indispensable.
- Binder Jetting appears promising for selected Ti applications, yet its industrial utility remains strongly dependent on successful debinding, sintering, densification, and finishing, which confirms its highly post-processing-intensive nature.
- Hybrid additive–subtractive manufacturing constitutes a particularly relevant strategy for Ti-alloys, since it combines the geometric flexibility of additive deposition with the dimensional accuracy and surface-quality benefits of machining.
- The principal unresolved constraints across all routes remain process repeatability, residual-stress control, tolerance stability, surface integrity, and the integration of deposition, heat treatment, machining, and monitoring into coherent industrial process chains.

Taken together, the findings of this article indicate that the future of Ti-alloy manufacturing lies not in the isolated optimisation of single processes, but in the coordinated integration of manufacturing and post-processing stages into coherent process chains. The most promising direction is therefore the convergence of alloy design, additive processing, hybrid manufacturing, and post-processing science within digitally assisted production environments. In such systems, real-time sensing, simulation-based planning, predictive modelling, and closed-loop control may help to reduce defects, improve dimensional stability, and strengthen process consistency. At the same time, the review makes clear that technological maturity remains uneven across the different AM routes, and that industrial implementation still depends heavily on costly downstream operations and specialist expertise. For this reason, the broader adoption of Ti-alloys will require not only better machines and better alloys, but also more standardised terminology, more reproducible processing windows, and stronger links between materials science and manufacturing engineering. Ultimately, the central conclusion of the present review is that post-processing is the key bridge within the integrated process chain between the promise of advanced Ti manufacturing and the delivery of components that are genuinely fit for demanding aerospace, biomedical, and high-performance engineering applications.

Author Contributions

Conceptualisation: A.G.P. and A.P.M.; methodology: A.F.V.P. and M.L.S.B.; validation: A.P.M.; formal analysis: A.A. and M.S.; investigation: A.A. and M.S.; data curation: A.F.V.P.; writing—original draft preparation: A.A., M.S. and A.F.V.P.; writing—review and editing: A.F.V.P.; visualisation: A.G.P.; supervision: M.L.S.B.; project administration: A.P.M.; funding acquisition: A.G.P. All authors have read and agreed to the published version of the manuscript.

Funding

The work is developed under the “DRIVOLUTION—Transition to the factory of the future”, with the reference DRIVOLUTION 02/C05-i01.02/2022, research project no. 23, supported by European Structural and Investments Funds with the “Portugal2020” program scope.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data was created.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. PRISMA 2020 Flow Diagram for New Systematic Reviews, Which Included Searches of Databases and Registers

This section presents the PRISMA 2020 flow diagram used to document the identification, screening, eligibility assessment, and final inclusion of studies considered in the present systematic review. The diagram supports methodological transparency, traceability, and reproducibility in accordance with the PRISMA 2020 framework.

The systematic search strategy was developed to identify peer-reviewed literature published between 2010 and 2025 concerning the manufacture and post-processing of Ti-alloys, with particular emphasis on additive manufacturing, hybrid manufacturing routes, and the resulting process–structure–property relationships. To ensure thematic precision, the search combined predefined keyword groups related to Ti-alloy systems, advanced manufacturing technologies, and post-processing or performance-related aspects, using Boolean operators and application to title, abstract, and keyword fields. The complete literature selection procedure is illustrated in the flowchart presented in Figure A1.

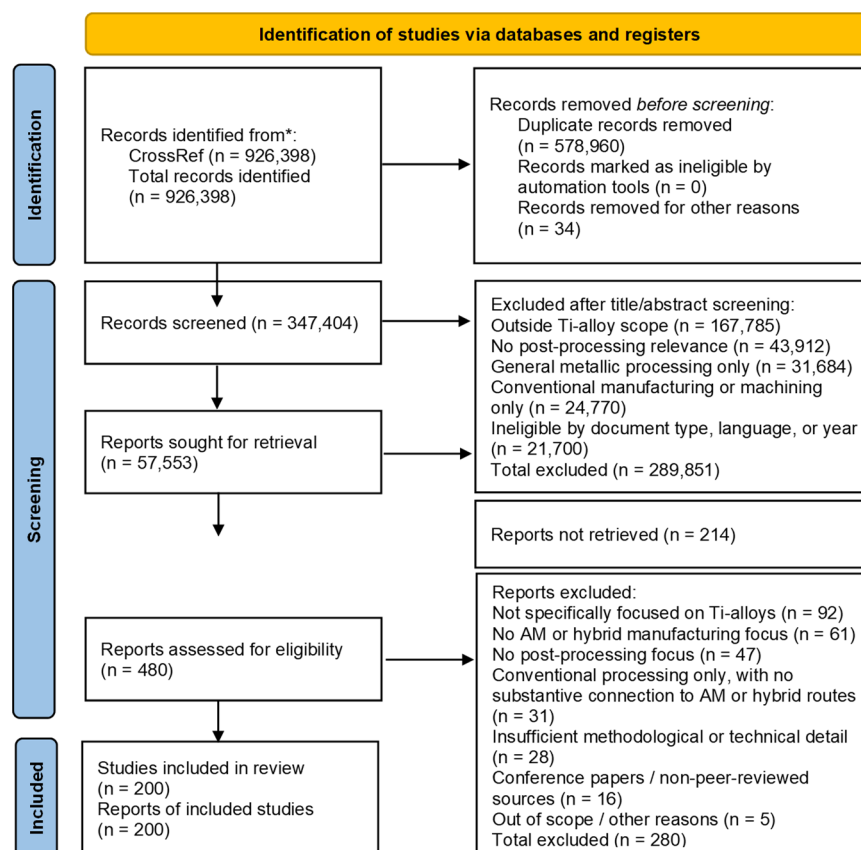


Figure A1. PRISMA2020 flowchart for the Ti-alloys AM study.

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