

# Resource efficiency in high-value material manufacturing with directed energy deposition

Jacques Strauss<sup>1,2</sup>, Devon Hagedorn-Hansen<sup>1,2\*</sup>, and Thorsten H. Becker<sup>3,4,5</sup>

<sup>1</sup>HH Industries, Somerset West, South Africa

<sup>2</sup>Industrial Engineering Department, Stellenbosch University, South Africa

<sup>3</sup>Centre for Materials Engineering, University of Cape Town, South Africa

<sup>4</sup>Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa

<sup>5</sup>eNtsa, Nelson Mandela University, South Africa

**Abstract.** Manufacturing high-value materials often yields excessive waste, high costs, and lengthy lead times using traditional methods. Directed Energy Deposition (DED) offers a sustainable alternative by reducing material waste, machining time, and tool consumption. This study demonstrates the cost and time efficiency benefits of DED over traditional manufacturing through an Inconel 625 case study. It was found that using DED can improve lead times, part functionality, and resource efficiency due to its wire feedstock flexibility and multi-material capabilities.

## 1 Introduction

Advanced manufacturing faces critical challenges when working with high-value materials (HVMs), which are defined by their ability to withstand extreme environments through properties such as high strength, toughness, and resistance to wear, temperature, and corrosion. These qualities make HVM, high-performance materials, essential to aerospace, defence, nuclear, and oil and gas industries. The desirable properties of high-value materials (HVM), such as high strength and toughness, resistance to wear, and corrosion resistance, make them inherently expensive and often involve long lead times for procurement and subsequent part fabrication. The subtractive nature of traditional manufacturing poses additional challenges, as it results in significant material waste, with the bulk of the costly material being removed during the process. The hardness and durability of these high-value materials increase machining time and tool wear, thereby further driving up production costs and resource consumption [1].

Directed Energy Deposition (DED) offers a practical alternative; the DED process involves building 3-dimensional parts layer by layer by depositing a wire or powder material feedstock and melting it with a focused energy source, such as a laser, arc, or electron beam source [2]. By manufacturing near-net shape components with DED, the material waste can be minimised as reliance on extensive machining is reduced. Furthermore, providing near net shape feedstock for machining, only semi-roughing and finishing machining operations are

---

\* Corresponding author: [devonh@hh.industries](mailto:devonh@hh.industries)

required, further decreasing machine cutting time and subsequent tool wear. DED's ability to produce multi-material and functionally graded components further enhances flexibility and efficiency, presenting an opportunity to address economic and sustainability concerns in manufacturing with high-value materials.

This paper demonstrates how DED can optimise the manufacturing of high-value materials by reducing costs, shortening lead times, and improving resource efficiency. The discussion develops as a structured argument that integrates insights from existing literature with a practical case study on an Inconel 625 component, used to illustrate the economic benefits of near-net shape manufacturing. The paper examines broader implications and challenges associated with implementing DED and introduces a decision flow diagram to guide the selection of appropriate manufacturing routes for high-value materials. The paper demonstrates how academic analysis can translate into practical guidance for manufacturing, highlighting the opportunities and limits of DED.

## 2 Advancing efficiency in DED manufacturing

The primary source of inefficiency in the traditional manufacturing of HVM lies in its inherently subtractive nature, which is commonly used. Large billets are required, which must then be extensively processed, leading to long machining times, significant material waste, and additional costs for consumables such as cutting tools. Near-net shape billets offer a proven solution to these inefficiencies by reducing the volume of feedstock required, thereby minimising material waste during finishing operations. Fewer finishing operations translate to shorter machining times and lower consumable usage. Traditional methods for producing near-net shape billets, such as forging, casting, and forming, have proven effective in many cases but come with specific limitations and challenges that can restrict their applicability [3, 4].

Forging and casting processes require substantial energy to heat materials to the high temperatures needed for deformation or melting, adding to production costs and environmental impacts [5]. These methods are typically economically viable only when producing large quantities of parts [3]. This poses a significant challenge for high-value materials, which are often required in lower quantities and, in many cases, as custom or one-off components. Certain materials are inherently unsuitable for forging, casting, or forming due to their specific physical, chemical, and mechanical properties. Each manufacturing process relies on materials meeting particular criteria, and when these are not met, alternative methods are required. This is especially true for HVM. High-temperature materials such as tungsten, niobium, and tantalum require extreme temperatures to reach a molten or plastic state [6, 7]. This makes them impractical or economically unfeasible to cast or forge due to the energy and specialised equipment required. High-strength, wear-resistant materials, such as certain tool steels, often exhibit brittleness that renders them unsuitable for forging or forming [8]. These materials are unable to undergo the plastic deformation required for forging without cracking or fracturing under intense pressures. Reactive metals, such as titanium, magnesium, and zirconium, have a strong affinity for oxygen, making them highly prone to oxidation at elevated temperatures. This property complicates processes, as maintaining the required inert atmospheres or vacuum environments significantly increases costs [11, 12, 13]. The materials science aspects of certain alloys further complicate their processing. Precipitation-hardened materials, such as certain grades of stainless steel and aluminium, rely on specific heat treatments to achieve their final mechanical properties. Exposure to the high temperatures required for casting or forging can disrupt the carefully controlled precipitation phases, leading to weakened material properties or reduced performance. Furthermore, some materials that undergo undesirable phase transformations during heating may experience significant degradation or loss of mechanical integrity,

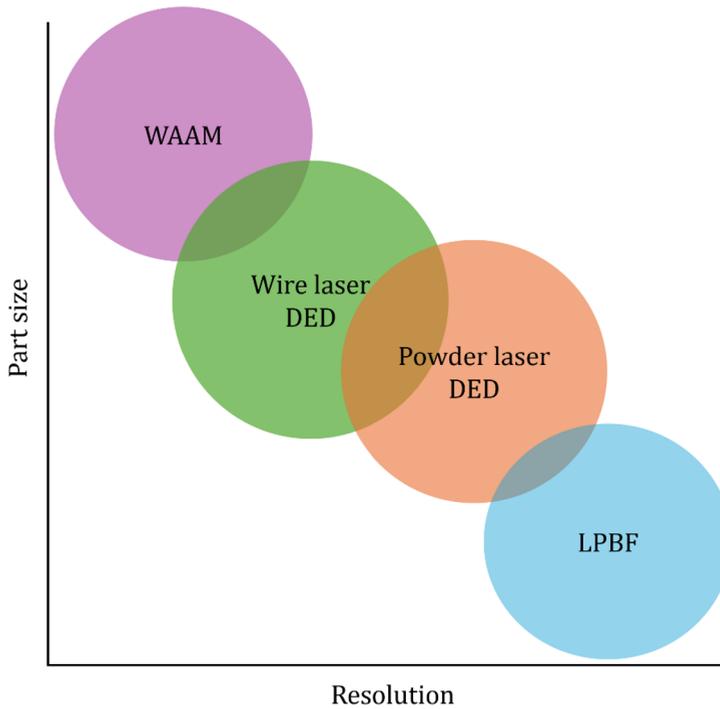
making these processes unsuitable. This could require additional costly post-processing heat treatments [14, 15, 16, 17].

These challenges highlight why the majority of high-value materials are often machined rather than processed using near-net shape methods. However, metal additive manufacturing (AM) offers a promising alternative, combining the advantages of near-net shape billets with reduced risks compared to other near-net shape manufacturing techniques. Metal AM typically employs precisely controlled localised heating in an inert atmosphere, ensuring material integrity. Its ability to efficiently produce custom or low-volume parts makes it particularly well-suited for high-value materials, addressing many of the economic and practical limitations of traditional methods.

Among AM technologies, DED and Laser Powder Bed Fusion (LPBF) are two of the most widely used and well-researched. While these technologies have distinct advantages and limitations, their application areas are beginning to overlap as the technologies evolve [18]. DED is conventionally preferred for larger, simpler geometries due to its higher deposition rates compared to LPBF, which is better suited for producing smaller, intricate parts at a higher resolution. DED technologies are further classified based on their energy source (laser, electron beam, or arc) and their feedstock (powder or wire) [2]. Each classification has specific strengths and limitations, with key factors including size, resolution, and cost. Wire Arc Additive Manufacturing (WAAM), a DED technology that uses an arc to melt wire feedstock, achieves high deposition rates but sacrifices part resolution. WAAM introduces significant thermal input, which can create challenges for heat-sensitive HVM. Laser-based DED typically offers superior localised heat control and higher resolution with slightly lower deposition rates, making it better suited for intricate or heat-sensitive materials. Laser-based DED systems can use either wire or powder feedstock, with powder systems typically achieving higher part resolutions, as shown in Figure 1 [2].

The choice between wire and powder-based laser DED significantly impacts cost, waste, and process efficiency. Wire feedstock holds several advantages over powder, particularly for HVM applications. Wire feedstock is generally significantly less expensive than powder due to the differences in their production processes. Powder is typically manufactured through the atomisation of rods, bars, or wires, a process that requires additional energy and specialised equipment, which contribute to higher costs [19]. This process not only adds cost but also leads to material waste, as a substantial portion of the powder produced does not meet the specific particle size distribution required for DED. Atomisation might not be a possible or economically feasible option for HVM with extremely high melting points, requiring the far more novel, costly alternatives like grinding to reach the necessary particle size [20].

Powder-based systems face inherent challenges that add complexity and cost to their operation. During the printing process, material losses often occur due to overspray and the effects of radiation pressure from the energy source [19]. Powder feedstock also poses inhalation hazards that demand specialised ventilation, protective equipment, and containment measures [21, 22]. These factors make powder-based systems significantly more costly and challenging compared to wire-based DED. Wire-based DED is safer, simpler, and more economical to implement in industrial settings. While powder feedstocks are more suitable for applications requiring high geometric precision, wire feedstock's cost efficiency and reduced waste make it the preferred choice for most HVM applications, especially when minimising material loss is a priority.



**Fig. 1.** Metal additive manufacturing size vs resolution.

The relative costs of billet, wire, and powder feedstocks further highlight the economic advantages of wire-based DED for high-value materials. Billet feedstock is the least expensive, followed closely by wire, while powder is significantly more costly. The cost difference between billet and wire is relatively modest, making wire-based DED an attractive alternative for near-net shape manufacturing. The gap between wire and powder is substantial, with powder feedstock often costing two to three times as much as wire. This disparity becomes even more pronounced for HVMs, which are challenging to process and require specialised methods for powder production. Although the upfront cost of wire feedstock may be slightly higher than that of a raw billet, the significant cost savings emerge during the production of near-net shape billets, drastically reducing the cost and time required for extensive machining. This reduces both production time and the consumption of costly carbide tools and bits. Machining time and tool wear account for a considerable portion of the cost of manufacturing high-value material components of the total production expense [23, 24]. By reducing the billet size to near-net shape, wire-based DED directly cuts down on these machining requirements, offering substantial cost savings while streamlining the production process.

Beyond the direct manufacturing costs, wire-based DED offers significant logistical and supply chain benefits for HVMs by simplifying inventory management and reducing lead times. Traditionally, manufacturing companies face logistical and financial challenges when maintaining billet inventories to accommodate a range of possible parts. They must either stock large billets, leading to excessive material waste during machining, or hold multiple billet geometries, requiring substantial storage space and capital investment [25]. These issues become even more pronounced when working with costly HVMs. HVM billets are therefore often custom-ordered and imported for specific jobs, resulting in high costs and lengthy lead times. Wire feedstock offers a more practical alternative as it's more commonly available in standard spools, it is easier to store and more flexible because manufacturers can use only the amount of wire needed to produce the near-net shape billet and retain the rest of

the spool for future use. This approach minimises reliance on specialised suppliers and shortens production cycles, providing a responsive, cost-effective solution for HVM components.

It is evident from the discussions above that wire-based laser DED offers the potential to enhance cost-effectiveness and efficiency in the manufacturing of HVMs. Beyond the immediate advantages of cost savings, reduced waste, and logistical benefits, DED features inherent capabilities that can further improve the manufacturing process. Its design flexibility allows for the creation of complex internal geometries, such as conformal cooling channels, which enhance thermal management and performance in demanding applications. DED's multi-material capabilities facilitate the production of functionally graded materials (FGMs), where material properties can be customised within a single component. This not only boosts performance but also lowers costs by strategically placing high-value materials only where they are required. These unique characteristics unlock a range of novel functionalities, further affirming wire-based laser DED as an innovative and highly effective solution for the manufacture of HVM components.

### 3 Case study: Inconel 625 part

This case study focuses on an Inconel 625 cup used in the medical isotope production industry. The Inconel cup, a round enclosed structure with a diameter of approximately 60 mm (Figure 2), is traditionally manufactured through a subtractive process of procuring bulk stock and machining this to the desired geometry. In particular, this involves machining the part from a 1-meter-long, 60 mm diameter solid round bar, yielding approximately 45 thin-walled cups, as seen in Figure 4. Additional operations include drilling holes, brazing a stainless-steel port, and attaching a flat sheet of Inconel to enclose the capsule. The traditional process is highly material-intensive, with approximately 88% of the billet's original volume ( $54.5 \text{ cm}^3$  of  $62.2 \text{ cm}^3$ ) wasted as chips during machining. This method incurs high costs due to tool wear and extended machining times. The billet costs are approximately R 1 million (R 22,300 per part) and have a lead time of 1–2 months. These inefficiencies highlight the need for a more resource-efficient manufacturing approach.



**Fig. 2.** CAD of Inconel cup.

Using DED, the Inconel cup can be produced as a near-net shape part, thereby significantly reducing material waste and machining requirements (with the near net shape billet having a volume of  $38.2 \text{ cm}^3$  compared to the final part volume of  $7.7 \text{ cm}^3$ ). The design incorporates a stainless-steel (SS316L) base section, with Inconel 625 deposited only in critical areas as required, as seen in Figure 3. The stainless steel section provides sufficient material for clamping for post-machining operations, while its lower cost and ease of machining further enhance overall efficiency. The typical lead time for the wire feedstock is 1-2 weeks. The part is printed on a Meltio M450 in approximately 4 hours. After band-sawing

it free from the baseplate, the total cost per part, including materials and processing, is R 6,092. While additional machining is required to finalise the DED part, its cost remains significantly lower than the R 22,300 billet price for the traditionally manufactured part, offering substantial cost savings.



**Fig. 3.** DED part after printing (left) and DED part after band sawing from the baseplate (right).



**Fig. 4.** Traditionally manufactured Inconel cup on 1 meter billet (left) vs DED near-net-shape billet after machining (right).

The case study illustrates the substantial benefits of utilising wire-based laser DED for manufacturing high-value material components, as can be seen in table 1. By making use of a near-net shape design, DED significantly reduces material waste by depositing material only where it is needed. In contrast, traditional subtractive methods result in considerable waste, with approximately 54.5 cm<sup>3</sup> of the original billet volume lost as chips compared to just 30.5 cm<sup>3</sup> for the near net shape billet. The incorporation of SS316L in non-critical clamping regions highlights the strategic use of cost-effective materials, further enhancing efficiency without compromising functionality. Beyond material efficiency, DED drastically reduces machining requirements. While post-machining is still necessary to achieve the final geometry, the time and tool wear associated with roughing milling operations significantly contribute to the cost [24].

This reduction not only decreases operational costs but also extends tool life, contributing to overall resource efficiency. Another critical advantage of DED is its reliance on wire feedstock, which eliminates the need for large custom billets. This reduces lead times from months to weeks and introduces greater flexibility for accommodating design modifications or new iterations. Combined with the rapid printing time of approximately four hours per part, DED offers a streamlined and adaptable manufacturing process. Collectively, these

benefits align with the broader objectives of sustainable and cost-effective manufacturing. By minimising material waste, reducing machining time, and optimising resource use, DED demonstrates its potential to transform the production of high-value material components while achieving significant economic and environmental gains.

**Table 1.** Comparison of traditional and DED approach.

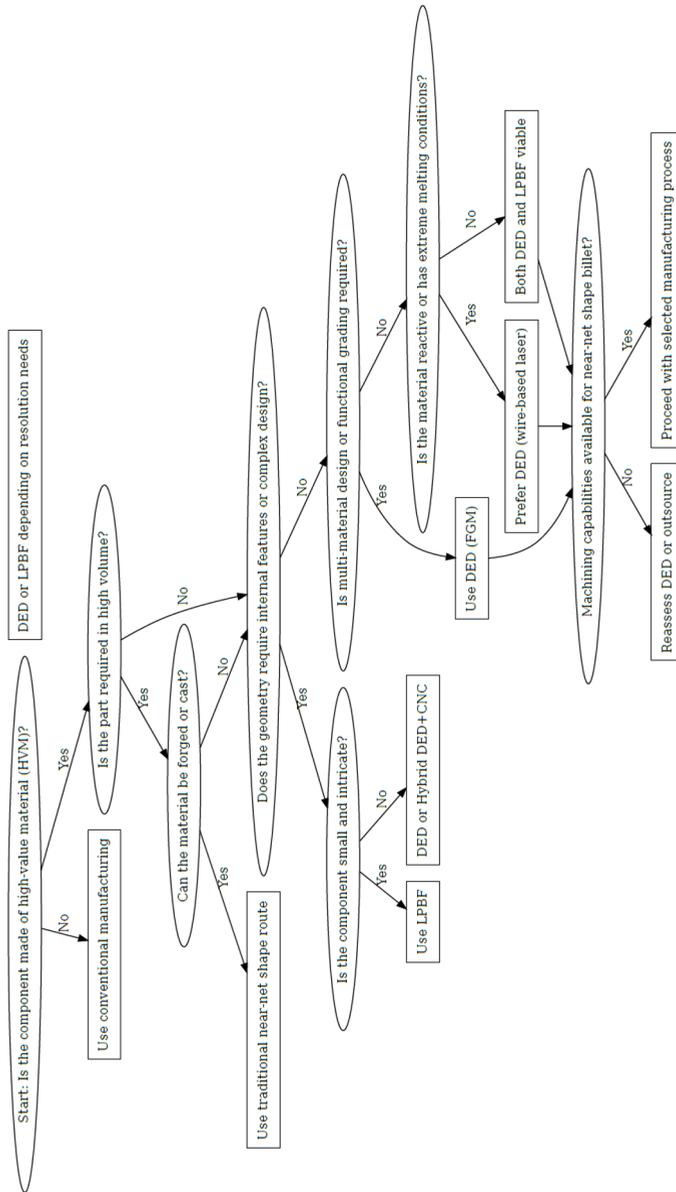
	Material Lead time	Material Cost	Waste
Traditional	1-2 months	R 22,300	54.5 cm <sup>3</sup>
DED	1-2 weeks	R 6,092	30.5 cm <sup>3</sup>

## 4 Implications, challenges, and considerations for high-value material manufacturing

HVM manufacturing presents unique opportunities and challenges, particularly when making use of advanced techniques like DED. Figure 5 illustrates a decision flow for selecting the appropriate manufacturing method based on part requirements and material characteristics. This section expands on the implications, challenges, and key considerations for optimising these methods.

The potential cost savings from DED can be substantial, particularly for parts that involve significant machining or feature complex internal geometries. However, determining the appropriate manufacturing method requires a careful evaluation of part geometry, size, and material properties. Larger, more complex components align well with DED's capabilities, while smaller, highly detailed parts may be better suited to technologies like LPBF. Material selection further impacts feasibility, as feedstock availability, cost, and lead times must also be considered. While near-net shape manufacturing reduces machining time and material waste, post-processing may still be necessary to achieve critical tolerances and desired surface finishes.

A distinctive advantage of DED lies in its ability to enable FGM designs, where material properties can be tailored within a single part. For example, high-value materials such as Stellite can be strategically placed in areas requiring wear resistance, while materials like copper can be used to enhance thermal conductivity elsewhere in the same part. This design flexibility allows manufacturers to optimise and enhance performance while reducing overall material costs. However, implementing FGMs introduces additional challenges, including the need to address chemical compatibility, manage potential galvanic corrosion, and incorporate interface layers where required to ensure reliable bonding. Small-scale testing is often indispensable to validate these designs before scaling to full production [26, 27]. Using DED to produce near-net shape billets offers considerable material efficiency but comes with its own machining complexities. These billets demand highly skilled machinists to program CNC machines effectively and set up fixturing for accurate machining. Interrupted cuts and chatter are common challenges, particularly if the billet design does not adequately account for machining operations [28, 29, 30]. To mitigate these issues, near-net shape designs must be carefully optimised to balance material efficiency with machinability. Advanced manufacturing techniques like DED have the potential to enhance HVM production by delivering cost savings, improving material efficiency, and enabling innovative designs. Implementing these technologies successfully requires a clear understanding of part-specific needs, process capabilities and material compatibility. By thoughtfully considering these factors, manufacturers can unlock the full potential of these innovations while mitigating risks and challenges.



**Fig. 5.** High value material manufacturing decision flow diagram.

## 5 Conclusion

This study highlights the potential of DED to significantly enhance resource efficiency in the production of HVMs. Wire-based laser DED addresses key inefficiencies in traditional manufacturing methods by minimising material waste, reducing machining time, and enabling cost-effective multi-material solutions, all while decreasing overall manufacturing lead times. The Inconel 625 case study illustrates these benefits in practice: compared to conventional billet machining, DED reduced lead times from 1–2 months to 1–2 weeks, lowered costs from approximately R 22,300 to R 6,092 per part and cut material losses from

54.5 cm<sup>3</sup> of wasted chips to 30.5 cm<sup>3</sup> in machining allowance. The case study demonstrates the substantial cost and resource savings through its near-net shape capabilities and strategic use of materials. Beyond these immediate benefits, DED supports innovative design possibilities, such as FGMs and multi-material configurations, which further optimise component performance and production efficiency. The successful implementation of DED requires careful planning and consideration. Challenges such as near-net shape billet machining, the complexities of FGM production, and the trade-offs between material efficiency and machinability must be addressed to fully realise DED's potential for HVM manufacturing. DED offers a pathway to more resource-efficient, cost-effective, and adaptable manufacturing practices, making it a compelling solution for advancing the production of HVM.

The active support and funding of the South African Department of Science, Technology and Innovation through the CSIR for the Collaborative Program in Additive Manufacturing, Contract No.: CSIR-CPAM-25-CON-IND-01, are gratefully acknowledged.

## References

1. T. Pereira, J.V. Kennedy, J. Potgieter, A comparison of traditional manufacturing vs additive manufacturing, the best method for the job, in Proceedings of the 4th Global Congress on Manufacturing and Management (GCMM-2018), Brisbane (2019).
2. D. Ahn, Directed Energy Deposition (DED) Process: State of the Art, *Int. J. Precis. Eng. Manuf.-Green Technol.* **8**, 703–742 (2021).
3. M. Daniele, C. David, R.C. Jonathan, Near Net Shape Manufacturing of Metal - A review of Approaches and their Evolutions, *Proc. Inst. Mech. Eng. Part B* **232**, 650–669 (2016).
4. N. Wan, Q.X. Zhuang, Z.Y. Chang, Z.F. Yi, An allowance optimization method for near net shape blade considering material saving, energy consumption and carbon emissions, *Int. J. Environ. Sci. Technol.* **20**, 4339–4354 (2023).
5. H. Wiebke, G. Alexander, G. Kathrin, U. Ulrich, Alloy and process design of forging steels for better environmental performance, *Sustain. Mater. Technol.* **34**, (2022).
6. L.K. Joseph, Forming and welding of niobium for superconducting cavities, in Proceedings of the Third Workshop on RF Superconductivity, Illinois (1988).
7. Z. Hong, C. Ming, S. Dayu, C. Qiang, L. Mengmeng, X. Han, Control of microstructure and properties for tantalum-tungsten alloy component manufacturing in cold forging and subsequent annealing process, in 4th World Conf. Mech. Eng. Intell. Manuf., Shanghai (2021).
8. M. Algarni, Enhancing the machinability and formability of tool steels through spheroidizing annealing heat treatment, *AIP Adv.* **14**, 10 (2024).
9. P. Armentrout, Chapter 6 - Reactivity and thermochemistry of transition metal cluster cations, in *Science and Technology of Atomic, Molecular, Condensed Matter & Biological Systems*, Elsevier (2010) pp. 269–297.
10. L. Popple, The oxidation of magnesium alloys in reactor atmospheres, *J. Nucl. Mater.* **8**, 1, 60–76 (1963).
11. J. Hassan, M.H. Idris, O. Ali, A review of ceramic shell investment casting of magnesium alloys and mold-metal reaction suppression, *Mater. Manuf. Process.* **28**, 843–856 (2013).

12. J. Gibbins, A. Stover, N. Krywopusk, K. Woll, T. Weihs, Properties of reactive Al:Ni compacts fabricated by radial forging of elemental and alloy powders, *Combust. Flame* **162**, 12, 4408–4416 (2015).
13. A. Mitchell, Melting, casting and forging problems in titanium alloys, *Mater. Sci. Eng. A* **243**, 1, 257–262 (1998).
14. C. Kai, F. Jiangkun, L. Xudong, Z. Jianing, J. Dian, S. Yuelin, C. Fulong, W. Jun, T. Bin, K. Hongchao, L. Jinshan, Microstructure and mechanical properties of nickel-based wrought superalloys under thermal-mechanical coupling: A review with Inconel 718, 625 as main case, *Prog. Nat. Sci.: Mater. Int.* **35**, 1, 65–82 (2025).
15. Z. Danial, K. Fuad, K. Farzad, M. Mehdi, H. Zuzana, Nickel-aluminum bronze (NAB) alloy design under two-steps casting and submerged friction stir processing, *Mater. Sci. Eng. A* **890**, (2024).
16. Z. Mohammad, M. Mohammad Ali, Intermediate annealing of severely deformed pure titanium by multi-directional forging: Effect on mechanical properties and microstructure, *Mater. Sci. Eng. A* **927**, (2025).
17. L. Xiang, D. Qipeng, H. Shihu, W. Xiaonan, Y. Ziwei, W. Zheng, L. Qingchun, N. Hiromi, Enhanced dispersoids precipitation, recrystallization resistance and mechanical properties of Al-Mg-Si-Cu-Mn alloy via Mo addition, *J. Mater. Sci. Technol.* **231**, 296–307 (2025).
18. B. Pushkal, S. Manu, J. Prashant K., R. Sandeep, A state of the art review on metal additive manufacturing: milestones, trends, challenges and perspectives, *J. Braz. Soc. Mech. Sci. Eng.* **46**, (2024).
19. R. Pengyuan, O. Yu, M. Jierui, L. Sheng, T. Zijue, W. Yi, L. Chu, L. Alex, O.J.P., Z. Yu, W. Haowei, W. Hongze, Metal powder atomization preparation, modification, and reuse for additive manufacturing: A review, *Prog. Mater. Sci.* **152**, (2025).
20. D. Harish Singh, P. Priti Ranjan, V. Koushik, Production of powders for metal additive manufacturing applications using surface grinding, *Manuf. Lett.* **32**, 54–58 (2022).
21. M. Bruna, M. Helena, Current development of the metal additive manufacturing sustainability - a systematic review, *Environ. Impact Assess. Rev.*, **112** (2025).
22. B. Moura, J. Rosero-Romo, H. Monteiro, A. Alberto, J. Laranjeira, S. Martin-Iglesias, U. Silvan, S. Lanceros-Mendez, D. Salazar, C. Martins, Addressing safety and sustainability issues in the development of nano-enabled Multi-Functional materials for metal additive manufacturing, *Sustain. Mater. Technol.*, **41** (2024).
23. J.-Y. Jung, Manufacturing cost estimation for machined parts based on manufacturing features, *J. Intell. Manuf.*, **13**, 227-238 (2002).
24. C. Pieter, O. Tiaan, D. Dimitri, S. Mike, Effect of milling strategy and tool geometry on machining cost when cutting titanium alloys, *South Afr. J. Ind. Eng.*, **26**, 3, 137-151 (2015).
25. J. Lessing, Analysing the effect of inventory management on operational performance in a manufacturing environment, North-West University, Potchefstroom (2021).
26. Y. Sanjeev, S. Liu, K. S. Rabesh, S. Anuj Kumar, R. Prashant, A state-of-art review on functionally graded materials (FGMs) manufactured by 3D printing techniques: Advantages, existing challenges, and future scope, *J. Manuf. Process.*, **131**, 2051-2072 (2024).
27. P. Azeem, R. B.M., Fabrication and mechanical properties of functionally graded materials: A review, *Mater. Today: Proc.*, **52**, 3, 379-387 (2022).

28. D. Mohammadreza Lalegani, S. Ahmad, Z. Ali, F. Mohammad, M. Mahmoud, A. M.K.A., B. Mahdi, A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process, *Adv. Powder Mater.*, **1,4** (2022).
29. S. Panagiotis, S. Thanassis, B. Harry, Hybrid Manufacturing Processes: an experimental machinability investigation of DED produced parts, *Procedia CIRP*, **101**, 218-221 (2021).
30. D. Jose Luis, N. Paulo Inforcatti, N. Pedro Yoshito, C. Reginaldo Teixeira, V. Jorge, d. Lopes, Hybrid manufacturing: a review of the synergy between directed energy deposition and subtractive processes, *Int. J. Adv. Manuf. Technol.*, **110**, 3377-3390 (2020).