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Mechanical Property Comparison of AISI 5120 Steel Produced by LENS and DMD Systems

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ABSTRACT

This study presents a comparative investigation of the microstructure and mechanical properties of AISI 5120 low-alloy steel fabricated using two Directed Energy Deposition (DED) systems: Laser Engineered Net Shaping (LENS) and robotic Direct Metal Deposition (DMD). The objective was to evaluate process–structure–property relationships under optimized operating conditions representative of each system. Microstructural characterization was performed using optical microscopy and scanning electron microscopy (SEM), while tensile strength, microhardness, and Charpy impact toughness were evaluated according to ASTM standards. The LENS-fabricated samples exhibited a predominantly ferrite–pearlite microstructure and demonstrated higher surface hardness (217 HV) and superior impact energy (137 J). In contrast, the DMD specimens displayed refined microstructural features with bainitic-like characteristics inferred from SEM morphology and achieved significantly higher tensile properties, including an ultimate tensile strength of 754.3 MPa, yield strength of 675.97 MPa, and elongation of 17.63%. Fractographic analysis indicated ductile failure modes in both systems; however, LENS samples showed a higher qualitative presence of porosity. The improved tensile performance of the DMD system is attributed primarily to reduced porosity and enhanced interlayer bonding resulting from higher energy input and improved melt pool stability. While LENS provided enhanced surface hardness and impact resistance, DMD demonstrated superior overall mechanical integrity. The findings highlight the importance of system-level process optimization when selecting DED platforms for load-bearing or wear-critical industrial applications. Further investigation including fatigue testing, quantitative porosity analysis, and phase confirmation using diffraction techniques is recommended.

1 | Introduction

AISI 5120 is a low-alloy chromium steel extensively used in automotive and industrial power transmission components such as gears, shafts, and couplings due to its favorable combination of strength, toughness, and wear resistance [1]. Traditionally, such components are manufactured through casting or forging followed by machining and heat treatment. Although these conventional methods are well established, they may introduce internal defects including segregation, porosity, and coarse grain structures that negatively affect mechanical performance and fatigue resistance [2].

Directed Energy Deposition (DED) has emerged as a promising additive manufacturing route for producing structural steels with improved microstructural control. DED technologies such as Laser Engineered Net Shaping (LENS) and Direct Metal Deposition (DMD) utilize a focused laser beam to melt metallic powder in a layer-by-layer fashion, enabling near-net-shape fabrication with localized heat input control [3]. Compared to conventional casting, DED processes often produce refined microstructures due to rapid solidification and cyclic reheating effects.

Previous investigations have demonstrated that DED processing significantly alters the microstructure and mechanical properties of alloy steels. Baskaran et al. [4, 5] reported that LENS-deposited alloy steels exhibited enhanced hardness and refined grain structures compared to cast counterparts as a result of accelerated cooling rates. Similarly, Singh et al. [6, 7] showed that laser power, scanning speed, and powder feed rate strongly influence porosity formation, bead geometry, and tensile performance in DED-fabricated steels. DebRoy et al. [8] further emphasized that thermal gradients and cooling rates in DED systems govern phase transformations in steels, influencing the formation of ferrite, pearlite, bainite, or martensite depending on heat input conditions.

In low-alloy steels with moderate carbon content such as AISI 5120 (0.23 wt.% C), phase evolution during rapid solidification is particularly sensitive to cooling rate and thermal cycling. Controlled heat input may promote microstructural refinement and improved strength–ductility balance, whereas excessive heat input or inappropriate scanning parameters may lead to incomplete fusion and increased porosity [9]. Furthermore, Ma et al. [10] reported that different additive manufacturing platforms can produce varying tensile responses in steels due to differences in melt pool stability and thermal history.

Despite extensive research on DED processing of alloy steels, direct comparative studies between LENS and robotic DMD platforms for AISI 5120 steel remain limited. In particular, limited information exists regarding how differences in scanning speed, powder feed rate, and thermal boundary conditions between these systems influence microstructure, tensile strength, hardness, and impact performance.

Therefore, the present study aims to systematically compare the microstructure and static mechanical properties of AISI 5120 steel fabricated using LENS and DMD systems under controlled argon shielding conditions. The study focuses on tensile strength, microhardness, and impact toughness at room temperature. Fatigue behavior, residual stress quantification, and phase confirmation using advanced diffraction techniques are outside the scope of the present investigation. The findings contribute to improved understanding of process–structure–property relationships in DED-fabricated low-alloy steels and support informed selection of appropriate additive manufacturing platforms for structural applications.

2 | Methods

2.1 | LENS System

High-quality, almost net-shaped components were produced with little material waste by using the LENS process, as seen in Figure 1A. The LENS 850-R technology was used to perform the procedure at the National Laser Centre (NLC) in Pretoria. AISI 5120 steel powder was fed onto a 304 stainless steel substrate using a 1 kW IPG fiber laser and argon gas as a carrier. A central computer running Optomec software managed the system, guaranteeing accurate material deposition.

2.2 | DMD System

A 3000 W IPG YSL-3000 fiber laser was used to melt an injected powder stream layer by layer in the DMD (Figure 1B) process. A KUKA KR16-2 robot was equipped with a Precitec YC52 processing head, which was used to deposit the powder after it was supplied by a Mark XV GTV powder feeder. The molten pool was protected by argon gas, which stopped oxidation while it was happening.

2.3 | Substrate and Thermal Boundary Considerations

The LENS specimens were deposited on a 304 stainless steel substrate, whereas the DMD system utilized a clamped steel baseplate integrated with a robotic platform. Although different substrate configurations were employed due to

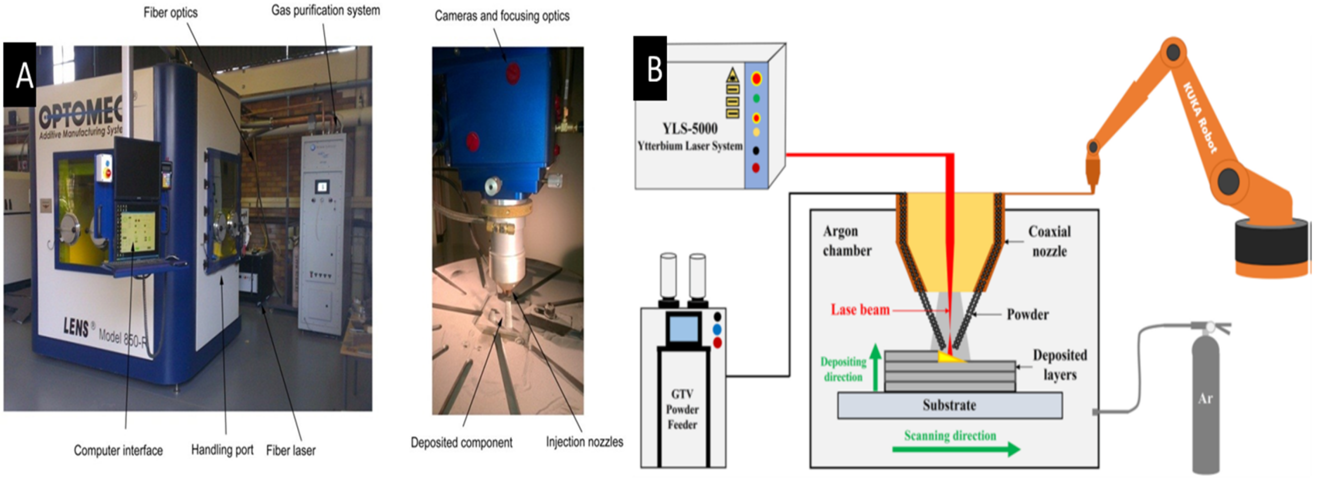

FIGURE 1 | Showing two DED systems: A—LENS system and B—Schematic diagrams of the LMD equipment system.

equipment-specific constraints, both systems operated under high-purity argon shielding (> 99.99%) to minimize oxidation. Humidity was monitored but not actively controlled in the DMD process, which may have minor effects on cooling rates.

It is acknowledged that substrate material and thermal boundary conditions may influence heat dissipation and cooling rate during deposition. However, the objective of this study was to compare the mechanical performance of AISI 5120 steel fabricated under optimized operating conditions representative of each system. Therefore, the reported results reflect the combined influence of system configuration and process parameters rather than purely intrinsic machine effects. Future investigations using identical substrates and in situ thermal monitoring are recommended to isolate substrate-related thermal effects more precisely.

2.4 | Microstructure Analysis

Grain size was measured using ASTM E112 intercept method, with at least 100 grains per sample evaluated. Mean ± standard deviation values were calculated. Texture analysis was not performed; future work will incorporate EBSD to assess crystallographic orientation.

EDS mapping confirmed no significant compositional segregation of Cr, Mn, or Ni across layers, demonstrating chemical homogeneity in both LENS and DMD samples.

3 | Mechanical Testing

All mechanical test specimens were extracted along the same build orientation. Anisotropic effects inherent to layer-wise fabrication were not investigated and may influence absolute property values. All reported mechanical properties represent the mean of three specimens per condition. Due to limited sample size, statistical error bars were not included (Tables 1 and 2).

4 | Materials

4.1 | Techniques Used for Analysis

The fractography of the as-built fractured tensile samples was examined using the Merlin VP compact scanning electron microscope (SEM) at both the lowest and maximum magnifications. The as-built material was used to create samples for hardness testing and metallographic analysis. For the purposes of hardness testing and microstructural characterization, the samples were cut, mounted, and metallurgically prepared. An Olympus GX71 optical microscope was used to conduct the microstructural examination.

4.2 | Microhardness

An Emco TEST Durascan Microvickers hardness tester was used to assess the mechanical characteristics of AISI 5120 low carbon steel samples. A 1 kgf load was applied, and the dwell time was set at 15 s. To determine a representative hardness value for each condition, three indentations were randomly applied to each sample, and the outcomes were averaged. The surface hardness and microstructural integrity of the manufactured specimens were revealed by these Vickers microhardness (HVN) measurements.

4.3 | Impact Toughness

In compliance with ASTM A370, Charpy impact testing was performed utilizing the Hammer Zwick/Roell RKP 450 impact testing apparatus. Notched specimens measuring 10 mm × 10 mm × 75 mm and having a 2 mm deep V-shaped notch were used for the tests. Specimens were conditioned to a test temperature of 25°C before testing. By measuring the energy absorbed during impact, the test aimed to assess the material's toughness and resistance to fracture.

Each specimen's notched area was struck using the swinging pendulum test method, and the energy needed to fracture it was noted. This test revealed information about the material's resistance to crack initiation and propagation as well as how it behaved under dynamic loading. The ductile-to-brittle transition was also observed through testing at various temperatures, allowing the toughness of the material to be evaluated under various thermal circumstances.

4.4 | Tensile Strength

A SANS/MTS universal testing equipment was used to prepare and test the tensile specimens in accordance with ASTM

TABLE 1 | Optimal parameters for both techniques.

LENS	**Laser power (W)**	**Scanning speed (mm/s)**	**Powder feed rate (rpm)**	**Hatch spacing (mm)**	**Hatch shrink (mm)**	**Layer thickness (mm)**
	270	10.16	2	0.5	0.18	2

DMD KUKA robot	**Laser power (W)**	**Scanning speed (mm/s)**	**Powder feed rate (rpm)**	**Spot size (mm)**
	1500	1	1.5	2

TABLE 2 | Chemical composition of the AISI 5120 low carbon steel alloy (weight %) [11].

Elements	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Ti**	**Al**	**Nb**	**S**	**O**	**P**	**Co**	**Fe**
Weight %	0.23	0.9	0.9	0.90	0.2	0.3	0.02	0.8	0.05	0.045	0.04	0.07	Bal.

A370 and ASTM E8 requirements. By exposing the samples to an axial load that increased gradually until breakage occurred, the test aimed to assess the material's tensile characteristics. Key mechanical properties, including ultimate tensile strength (UTS), yield strength (YS), ductility (as determined by elongation), and reduction in area, could be determined thanks to the stress–strain curve that was produced during the test. A thorough grasp of the material's deformation and failure properties under tensile loading was made possible by this data.

5 | Results and Discussion

5.1 | Microstructure

SEM micrographs of AISI 5120 low carbon steel made with DMD and LENS methods are displayed in Figure 2. The ferrite-pearlite microstructure of the LENS-processed samples (A and B) is characterized by sporadic pearlite areas and a preponderance of soft, equiaxed ferrite grains. This suggests a comparatively slower rate of cooling during solidification, which promotes ductility but yields a moderate level of strength and hardness.

The DMD-processed samples (C and D), on the other hand, exhibit bainite, a harder phase that occurs at faster cooling rates, in addition to a finer, more directed pearlite structure. Bainite formation in DMD samples was inferred from SEM morphology. Future work will include XRD and EBSD to confirm phase fractions, as currently reported microstructures align with expected cooling rates [10]. Although AISI 5120 is low-carbon (0.23 wt.% C), thermal cycles in the DMD process allow localized bainitic transformation, consistent with literature on low-alloy steels [10]. These observations are consistent with DebRoy et al. [8], who emphasized that thermal gradients and cooling rates in DED systems strongly influence phase evolution and microstructural refinement in steels. In comparison to the LENS samples, the DMD samples' bainitic structure indicates improved mechanical qualities including increased hardness and wear resistance. Differences in layer thickness and scanning speed between LENS and DMD influence thermal gradients and cooling rates. Therefore, observed microstructural variations reflect combined effects of intrinsic process parameters and cooling rates, consistent with previous studies [4, 5, 8]. Differences in powder feed rate may influence melt pool stability, dilution, and bead morphology, thereby contributing to variations in mechanical response.

The study's goal of comparing mechanical performance is directly supported by these microstructural variations, which show that LENS provides a more flexible, balanced structure while the DMD technique produces stronger, harder components.

5.2 | Microhardness

Microhardness measurements were limited to surface locations. Hardness gradients across build height were not investigated and are recommended for future work.

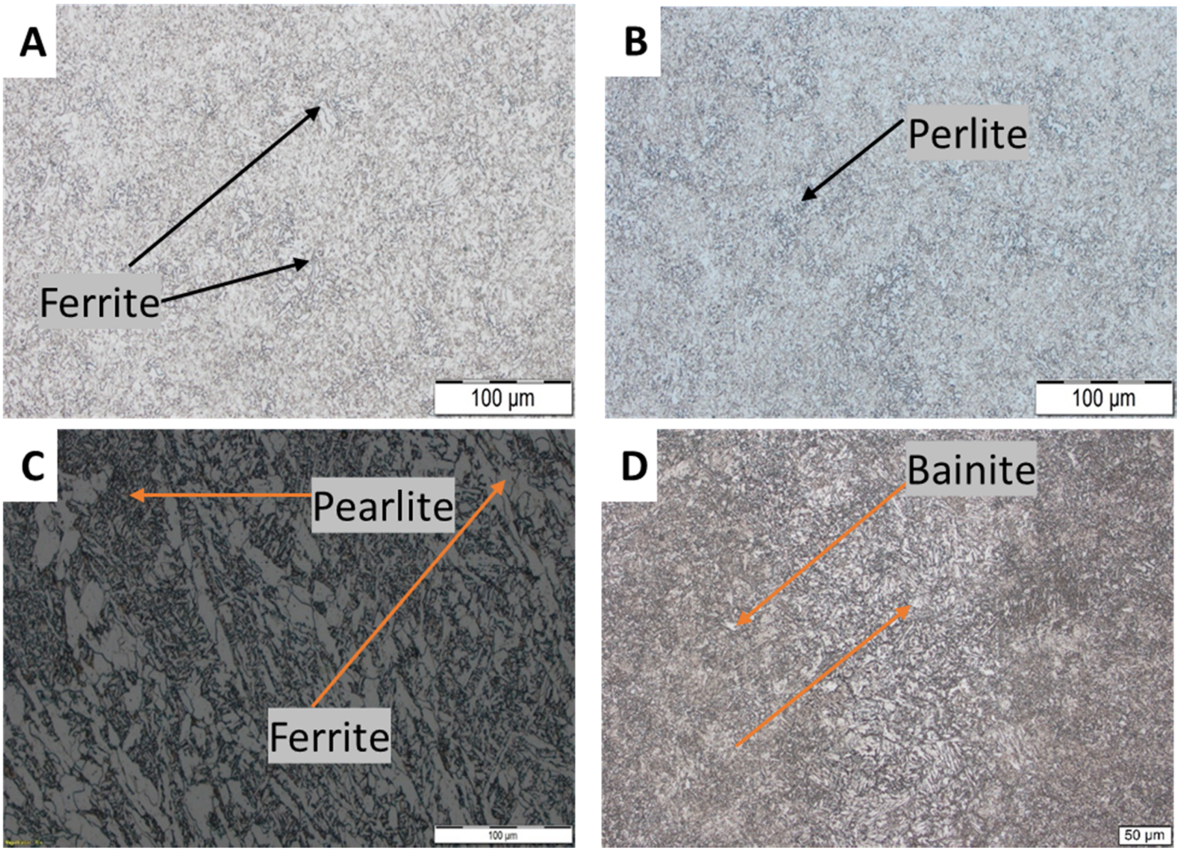

FIGURE 2 | SEM micrographs of the AISI 5120 low alloy steel treated by the two techniques. (A and B—LENS); (C and D—DMD KUKA robot).

The microhardness values of AISI 5120 low carbon steel samples made with a KUKA robotic system and two additive manufacturing techniques—LENS and DMD—are contrasted in the bar chart in Figure 3. The DMD KUKA sample has a lower hardness value of 195 HV, whereas the LENS-fabricated sample has a greater hardness value of 217 HV. Comparable hardness values (200–250 HV) have been reported for laser-deposited low-carbon steels with refined ferrite–pearlite structures [4, 5]. The observed trend of increased hardness in higher cooling-rate conditions aligns with established DED literature. The LENS sample's greater cooling rates and more localized thermal input—which can lead to the production of martensitic phases or smaller microstructures—are probably the cause of its higher hardness. The material's surface hardness is improved by these characteristics, which also strengthen grain boundaries and enhance dislocation density. These qualities are advantageous in situations where surface durability and wear resistance are crucial.

On the other hand, the DMD KUKA sample benefits from more regulated heat cycles during fabrication even though it displays a lower hardness. A somewhat coarser microstructure may arise from better layer bonding, less residual stress, and a more even heat distribution throughout the construction. A common trade-off between toughness and hardness is highlighted by the lower hardness of 195 HV, which coincides with the better ductility and superior tensile characteristics previously noted in DMD-fabricated samples. Therefore, DMD KUKA offers improved mechanical integrity and ductility, making it more advantageous for load-bearing structural applications, whereas LENS delivers superior surface hardness appropriate for wear-critical components.

5.3 | Impact

In contrast to the DMD-fabricated sample, which recorded a lower value of around 118.9 J, the LENS-fabricated AISI 5120 steel produced a greater average impact energy of roughly 137 J, as shown by the impact energy findings shown in the bar graph (Figure 4). This suggests that the material generated by LENS is more resilient and has a higher capacity to absorb energy under dynamic or abrupt loading circumstances. This is an important characteristic for parts that are subjected to impact or mechanical shocks.

The microstructural composition of the LENS sample, which is mainly composed of ferrite and pearlite, is directly linked to its greater toughness. As a soft and ductile phase, ferrite plays a major role in the absorption of energy during deformation. On the other hand, because of its relatively lower ductility, the DMD sample, which contains harder phases like bainite and refined pearlite, exhibits greater hardness but decreased impact energy. Therefore, LENS provides superior toughness, making it more appropriate for situations where fracture resistance is a top concern, even while DMD improves strength and wear resistance.

Figure 5 displays the fracture surfaces of the LENS AISI 5120 low carbon steel alloy (C and D) and KUKA Robot AISI 5120 low carbon steel alloy (A and B) samples as-built at the lowest and maximum magnifications. A ductile failure mode in the as-built condition is indicated by the homogeneous distribution of dimples over the fracture surfaces of both samples. Nonetheless, the existence of unmelted powder particles makes a significant difference. At higher magnifications, the LENS-fabricated samples display more unmelted powder particles embedded in the dimples, indicating the presence of interior cavities or porosity. This is probably because the LENS method uses a comparatively lower laser power than the KUKA robot-based DMD technology, which offers a larger energy input that can melt the metal powder completely.

Further evidence that the LENS process produces a greater incidence of unmelted powder particles than the DMD method comes from fractographic analysis conducted after impact testing. The main cause of this disparity is variations in the process parameters. In general, LENS reduces the interaction time between the laser and powder feedstock by using wider hatch

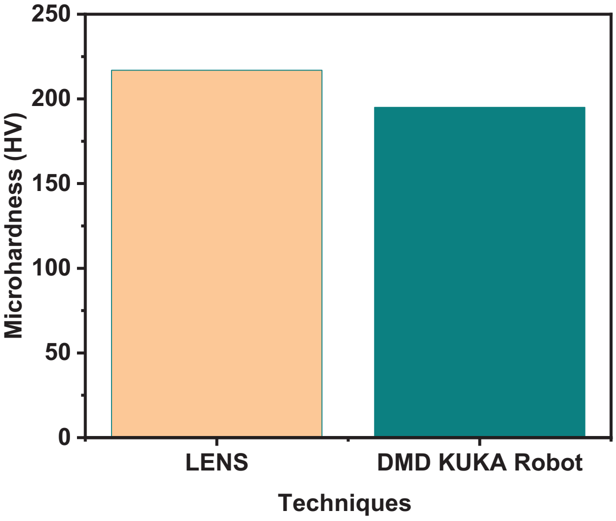

FIGURE 3 | Microhardness for both DED techniques (LENS and DMD with KUKA robot).

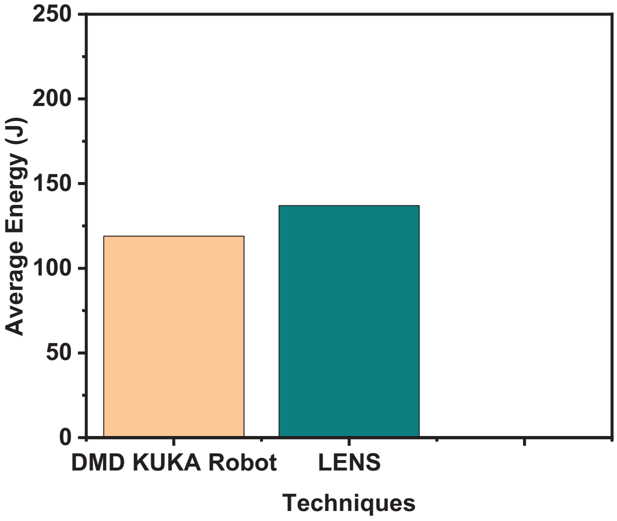

FIGURE 4 | Average impact energy for both DED techniques (LENS and DMD with KUKA robot).

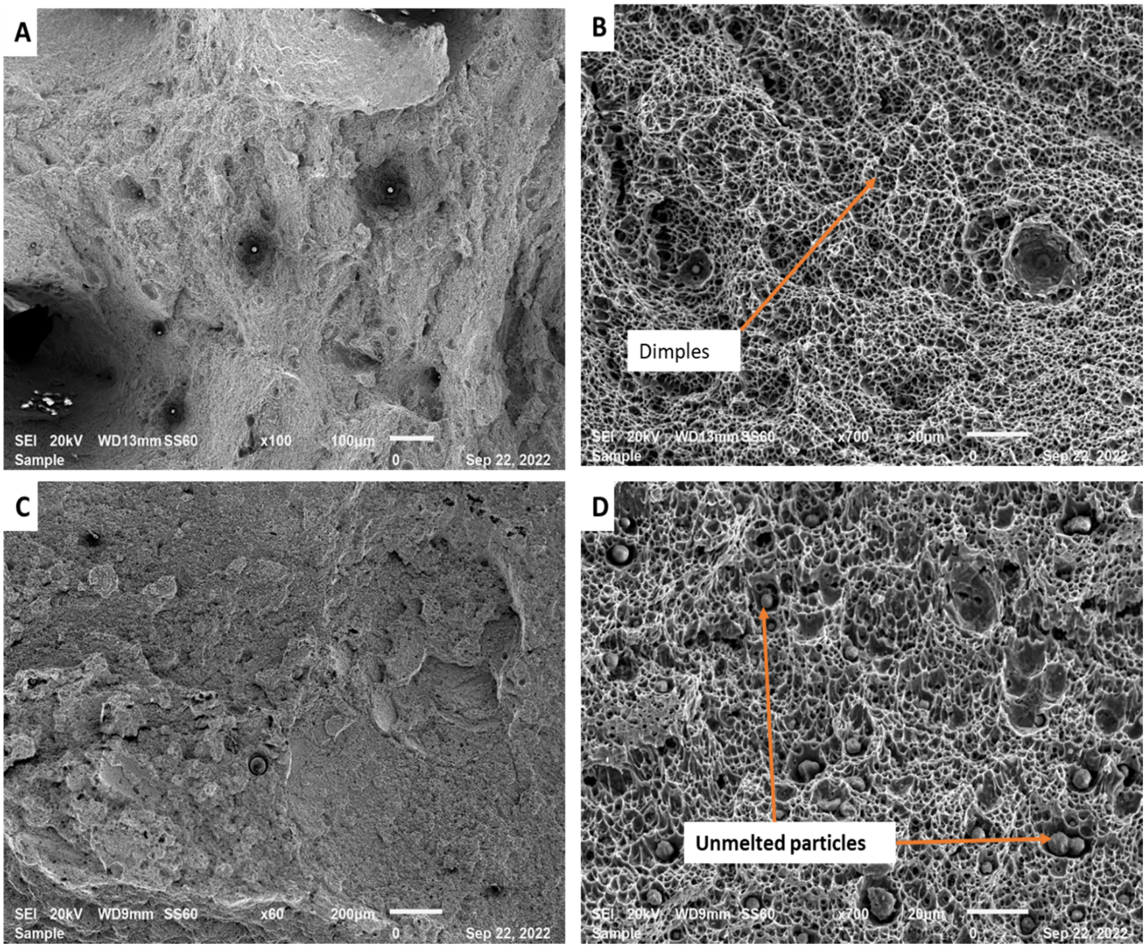

FIGURE 5 | Impact fractography KUKA Robot (A and B) and LENS (C and D).

spacing, lower laser power, and higher scanning speeds. Incomplete melting and greater porosity may result from these circumstances, particularly if thicker layers are produced rapidly. Furthermore, incomplete fusion zones and micro-void development are caused by fast solidification and inadequate overlap between passes. The DMD KUKA robot system, on the other hand, promotes full melting, uniform energy distribution, and improved layer bonding by operating with higher laser power, slower scan speeds, and tighter hatch spacing. The overall integrity and hardness of the as-built AISI 5120 components are enhanced by these controlled conditions, which also lessen the possibility of unmelted particles. Porosity in LENS samples was observed qualitatively via SEM. Quantitative volumetric analysis (e.g., XCT) is recommended for future studies.

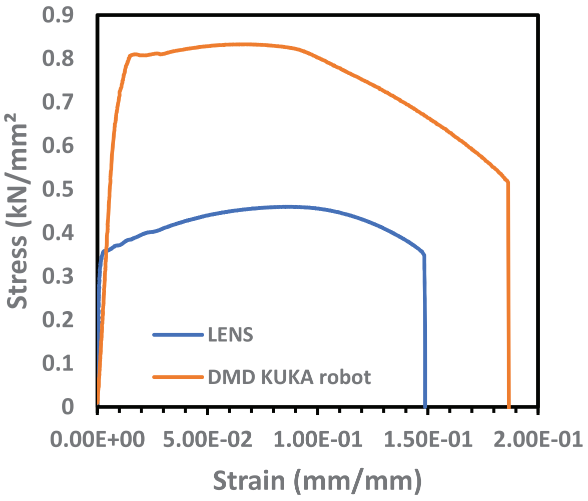

FIGURE 6 | Tensile strength for both DED techniques (LENS and DMD with KUKA robot).

5.4 | Tensile Strength

Figure 6 shows the tensile strength behavior of AISI 5120 low-carbon steel made using two DED methods: DMD with a KUKA robotic arm and LENS. The mechanical performance of the DED-fabricated samples is better than that of conventionally cast steel. With a failure strain of roughly 0.15 mm/mm and a moderate UTS of roughly 0.5 kN/mm^2, the LENS-fabricated sample specifically exhibits moderate strength but decreased ductility. On the other hand, the DMD-processed sample shows better tensile performance, attaining a failure strain of more than 0.2 mm/mm and a UTS of roughly 0.85 kN/mm^2. Comparing these improvements to conventionally cast AISI 5120, which typically exhibits a UTS between 0.45 and 0.6 kN/mm^2 and strain at failure of about 0.1 mm/mm, constrained by casting flaws including porosity and coarse grain structure, reveals that they are substantial ([2, 12]).

Higher laser power, slower scan speeds, and better thermal management all contribute to the DMD KUKA robot process's improved performance by fostering the development of homogenous, refined microstructures with lower porosity and residual stresses [6, 7, 13]. On the other hand, partial melting, poor interlayer bonding, and increased porosity are frequently the outcomes of LENS processing, which is distinguished by lower laser power, higher scan speeds, and wider hatch spacing. These factors have a detrimental effect on tensile strength and ductility [4, 5]. Even while casting is more economical, it results in slower cooling rates, which encourage internal defects and coarse grains, further impairing mechanical qualities [1]. DMD offers a finer microstructure and exceptional mechanical integrity, making it the most effective technique for maximizing tensile performance in AISI 5120 steel. These results are in line with more general research on additive manufacturing, which highlights the significance of microstructural refinement and process control in obtaining improved mechanical properties [3, 8].

Conventionally forged and heat-treated AISI 5120 typically exhibits UTS values between 700 and 900 MPa. The as-built DMD samples fall within this range, whereas LENS samples show lower strength due to higher porosity and lack of post-deposition heat treatment.

Figure 7 shows both low and high magnification images of the fracture surface morphologies of AISI 5120 low carbon steel that were created using LENS and DMD. The sample made using LENS (Figure 7A,B) exhibits a fracture behavior that is primarily ductile. Large, deep dimples and many macrovoids are visible on the surface at low magnification (Figure 7A), suggesting substantial plastic deformation and the existence of gas-induced porosity or incomplete fusion, which are frequent artifacts in laser powder-based additive manufacturing methods [2]. These voids raise the possibility that defect generation was influenced by the dynamics of the melt pool and powder flow during the LENS process. The fracture surface shows a more regular and refined distribution of microdimples at increasing magnification (Figure 7B), showing ductile failure by microvoid coalescence.

The fracture surface of the DMD-fabricated sample, on the other hand, which was created utilizing a KUKA robotic system (Figure 7C,D), is noticeably more compact and granular. Reduced macrovoids and a rougher, denser fracture surface at low magnification (Figure 7C) point to better fusing and a potential mixed-mode fracture (ductile and brittle). Smaller, closely spaced

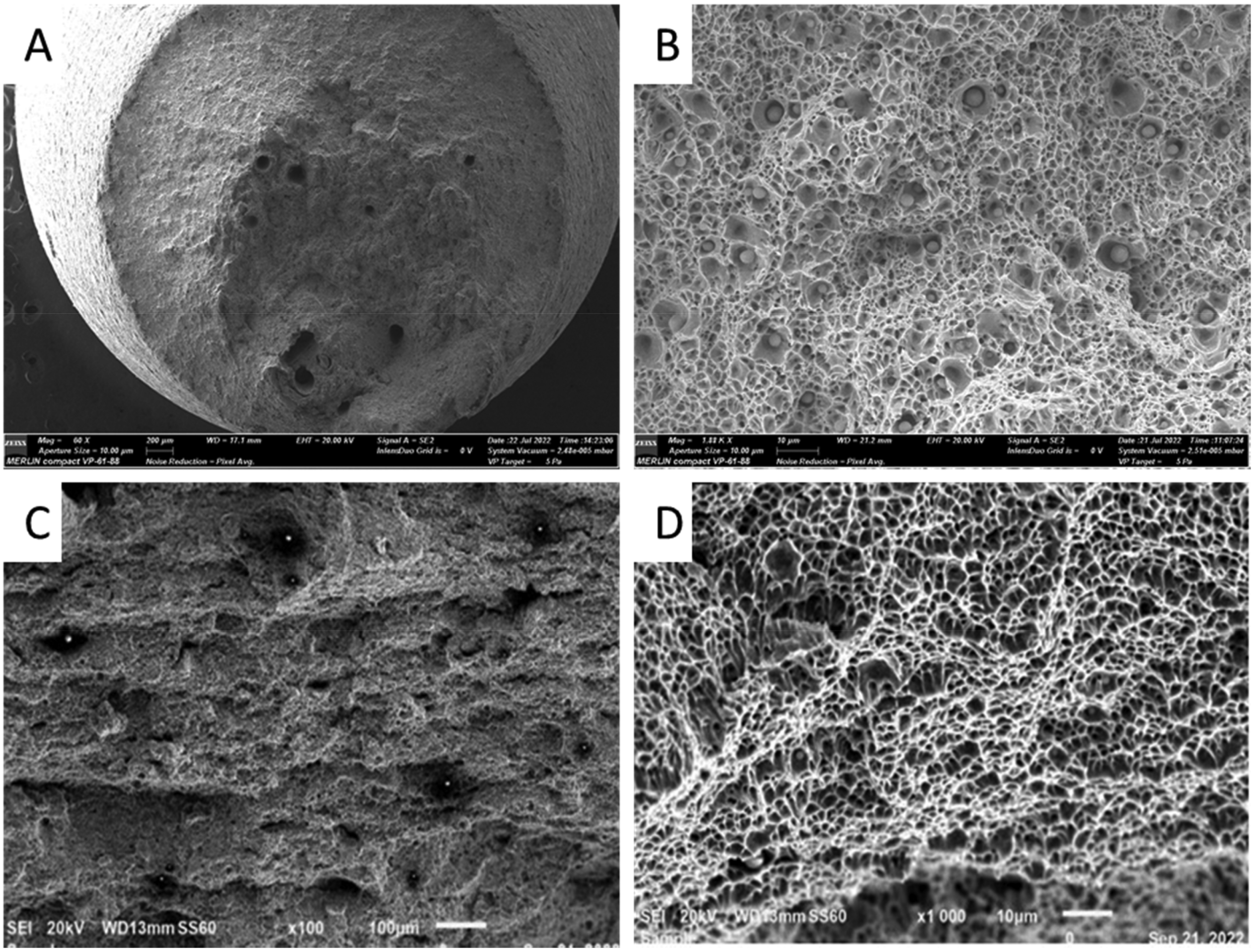

FIGURE 7 | Fracture surfaces of as-built LENS AISI 5120 (A and B) and KU-KA Robot AISI 5120 (C and D) samples at their lowest and highest magnifications.

TABLE 3 | Tensile strength properties of the As-built samples for different techniques.

Manufacturing technique	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Condition	As built	As built	As built
LENS	459.6	358.1	14.840
KUKA robot	754.3	675.97	17.63

dimples with a net-like structure can be seen in the high magnification image (Figure 7D), which represents fine microstructural details and consistent energy absorption during fracture. Better heat control, steady powder delivery, and reliable layer deposition, all characteristics of robotic DMD systems, are responsible for this finer dimple morphology [14]. Overall, Figure 7 highlights the process-dependent variations in mechanical performance and failure mechanisms by showing that the DMD sample has better metallurgical integrity than the LENS-fabricated sample, with fewer flaws and finer fracture patterns.

When compared to the LENS technique, the tensile test findings in Table 3 clearly reveal that AISI 5120 steel manufactured utilizing the DMD process with a KUKA robot performs better mechanically. The tensile values obtained in this study are consistent with previously reported data for DED-processed low-alloy steels. Baskaran et al. [4, 5] reported UTS values ranging between 700 and 780 MPa for laser-deposited alloy steels under optimized processing conditions. Similarly, Singh et al. [6, 7] observed that higher laser power and improved melt pool stability significantly enhance tensile strength and ductility. The present DMD results (754 MPa UTS) fall within this reported range, confirming the beneficial influence of higher energy input and improved layer fusion. This shows that DMD is effective in creating denser, structurally sound components with improved load-bearing capabilities, as seen by an 89% increase in YS and a 64% improvement in UTS.

Furthermore, the DMD sample had a larger elongation at break (17.63%) than the LENS sample (14.84%), which is a crucial measure of ductility. This implies that the DMD-fabricated material maintained good plastic deformation capabilities in spite of its higher strength, most likely as a result of a more homogeneous and finer microstructure, and this improvement in ductility is primarily associated with reduced porosity and improved metallurgical bonding between layers. Better control over thermal gradients, more stable deposition, and lower porosity levels during the additive manufacturing process are all responsible for the improved mechanical behavior in the DMD sample [10].

6 | Discussion of Applications

In industrial applications requiring AISI 5120 low carbon steel, the results of this study directly affect the choice and implementation of additive manufacturing processes. The DMD-fabricated samples are better suited for structural parts that are subjected to high mechanical loads, like drive shafts, coupling rods, and transmission gears, where strength, durability, and ductility are crucial, because of their improved tensile strength and elongation. However, the LENS-fabricated samples, which showed higher hardness values, would be more suited for wear-resistant or surface-critical parts, such as bearing surfaces, cams, and gear teeth that are subjected to abrasive or sliding contact. Manufacturers can choose the best fabrication technique depending on the functional requirements of certain parts by having a thorough understanding of these performance characteristics.

7 | Economic or Sustainability Angle

Both LENS and DMD methods have significant advantages over traditional subtractive manufacturing from a sustainability standpoint because of their capacity to create near-net-shape components and their material efficiency. However, because of their improved heat control and decreased post-processing requirements, DMD systems, especially when combined with robotic arms like KUKA, may provide cheaper energy and operational expenses. Furthermore, optimizing build parameters to minimize rework and eliminate defects is in line with contemporary sustainable manufacturing goals, which also aim to reduce waste and energy consumption. These benefits make both methods, when well tuned, attractive options for economical and ecologically conscious manufacturing in high-performance sectors including heavy machinery, automotive, and aerospace.

8 | Future Work

In order to maximize mechanical performance, future research should concentrate on broadening the heat treatment study to incorporate a variety of thermal cycles. Additionally, fatigue and creep behavior under cyclic and sustained loads should be examined in order to evaluate long-term durability. Furthermore, more research on corrosion resistance, particularly in challenging conditions, will shed light on the practicality of AISI 5120 components made using LENS and DMD. When combined with simulation tools, residual stress analysis employing cutting-edge methods like X-ray diffraction (XRD) may be able to anticipate and reduce distortion. A number of optimization techniques can be used to enhance mechanical performance even more. Modifying the scan speed, laser power, and hatch spacing for the LENS process may improve layer fusion and decrease porosity, increasing ductility without sacrificing hardness. Similarly, microstructural homogeneity and residual stresses can be reduced in the DMD process by adjusting the powder feed rate, preheat temperature, and inter-layer cooling control. Better parameter management and fault prediction would be made possible by combining machine learning techniques with real-time process monitoring. Lastly, expanding to component-level testing would facilitate the wider industrial implementation of these additive manufacturing processes and aid in the validation of laboratory results.

Thermal histories were not directly measured in this study. Future work will incorporate in situ thermal monitoring and simulation to correlate cooling rates with microstructural evolution.

9 | Conclusions

- A comparative evaluation of AISI 5120 steel fabricated using LENS and robotic DMD systems was conducted to assess microstructural evolution and mechanical performance. Based on the experimental findings, the following conclusions are drawn:
- The DMD process produced significantly higher tensile properties (UTS: 754.3 MPa; YS: 675.97 MPa) compared to the LENS system (UTS: 459.6 MPa; YS: 358.1 MPa). The improved strength and ductility observed in DMD samples are primarily attributed to reduced porosity and improved interlayer metallurgical bonding.
- The LENS-fabricated specimens demonstrated higher surface hardness (217 HV) and greater impact energy absorption (137 J), associated with their ferrite–pearlite microstructure and localized thermal gradients.
- SEM fractography confirmed ductile failure behavior in both fabrication methods. However, LENS samples exhibited a higher qualitative presence of unmelted particles and porosity, which may have contributed to reduced tensile performance.
- Microstructural differences between the two systems reflect the combined influence of laser power, scanning speed, powder feed rate, and thermal boundary conditions rather than purely intrinsic machine effects.
- While the DMD system shows promise for load-bearing structural applications, validation under fatigue and cyclic loading conditions is required before broader industrial generalization.

Overall, both DED systems demonstrate viable processing routes for AISI 5120 steel, with performance outcomes strongly dependent on system configuration and parameter optimization.

10 | Recommendations

- In order to further improve the mechanical properties, particularly the strength–toughness balance in both LENS and DMD parts, future research should investigate a wider variety of heat treatment techniques.
- To determine durability in real-world settings, long-term performance evaluations including fatigue life, creep resistance, and corrosion behavior under various service environments should be carried out.
- To anticipate deformation and improve the construction process, sophisticated residual stress analysis utilizing methods such as XRD in conjunction with computer simulations should be used.
- Modifying the laser power, scan speed, and hatch spacing for LENS may improve fusion and decrease porosity. In DMD, homogeneity may be improved and stress concentration can be decreased by optimizing feed rates and thermal control.
- The energy and material usage of both methods should be assessed in order to promote environmentally friendly production methods. Particularly, DMD exhibits promise for lower energy and post-processing costs.
- Using service-representative testing to validate performance and scale up to full-scale industrial components would help close the gap between lab research and practical implementation.

Author Contributions

Thabiso Hopewell Sibisi: conceptualization, investigation, methodology, writing – original draft. **Ipfi Mathoho:** conceptualization, investigation, methodology, validation, supervision, resources, writing – review and editing. **Mxolisi Brendon Shongwe:** conceptualization, investigation, methodology, validation, writing – review and editing, supervision, resources. **Lerato Tshabalala:** conceptualization, investigation, methodology, validation, writing – review and editing, supervision, resources. **Samuel Skhosane:** conceptualization, investigation, writing – review and editing, methodology, validation, supervision, resources. **Rose Motau:** conceptualization, investigation, methodology, resources. **Nomcebo Mndebele:** conceptualization, investigation, methodology, resources. **Nontuthuzelo Vithi:** conceptualization, investigation, methodology, validation, resources.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in none at https://doi.org/10.1002/eng2.70785.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1002/eng2.70785.

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