

MICROSTRUCTURAL AND HARDNESS CHARACTERIZATION OF STAINLESS STEEL 316L/ MILD STEEL ER70-S SANDWICH STRUCTURES FABRICATED BY WIRE- BASED DIRECTED ENERGY DEPOSITION

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ABSTRACT

Multi-material additive manufacturing is gaining attention for its ability to combine the strengths of different materials into a single part. In this study, a sandwich structure made of 316L stainless steel and ER70-S mild steel was created using a Meltio M600 laser-based wire Directed Energy Deposition (W-DED) system. Both single-material samples and the multi-layer sandwich structure were produced using the same processing settings. Optical microscopy was used to study the shape and interface of the deposited layers. Further microstructural analysis was done with scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and electron backscatter diffraction (EBSD). The ER70-S area showed a ferritic microstructure with lamellar pearlite, while the 316L area consisted mostly of austenitic grains. EDS analysis showed a gradual change in element concentrations across the interface, particularly the movement of chromium and nickel from stainless steel into mild steel. Microhardness tests (HV0.1) revealed a sharp hardness increase in the interface, suggesting microstructural transformation and element mixing. These results show that wire-based DED can form stable bonds between stainless steel and mild steel in multi-material parts.

KEYWORDS

Directed Energy Deposition, Multi-Material Additive Manufacturing, Stainless Steel 316L, ER70-S Mild Steel, Microstructure, Microhardness.

1 INTRODUCTION

Direct Energy Deposition (DED) is an additive manufacturing (AM) process that uses lasers, electric arcs, or electron beams as a source of energy to create a melt pool to which materials

are simultaneously introduced in powder or wire form [Das 2023], [Bochnia 2024]. These processes are typically classified based on the use of energy source Wire Arc Additive Manufacturing (WAAM) uses an arc, Laser-Direct Energy Deposition (L-DED) uses laser, and Electron Beam Additive Manufacturing (EBAM) uses an electron beam [Kang 2025], [Joshua 2024]. DED is widely used for fabricating new components, repairing damaged parts, and functional coatings [Perini 2024]. Wire-DED processes have emerged as a research focus due to their approximately 100% material utilization, economical feedstock costs compared to powders, and good deposition efficiency. Compared with powder, the wire DED provides higher deposition rates, and while producing the larger components, the risk of oxidation and contamination is less; furthermore the metal wires are generally considered safer in industrial workshops than fine metallic powders. [Perini 2024].

The step towards Multi-Material Additive Manufacturing (MMAM) is demanded to produce components that can withstand and operate efficiently in extreme conditions, and possess multifunctional properties, such as high strength combined with corrosion resistance. To overcome the isotropic performance limitations of monolithic materials produced by traditional manufacturing processes, the shift from manufacturing homogeneous parts to designing integrated functional systems [Perini 2024], [Stradomski 2022]. Despite its advantages, MMAM has notable limitations, particularly in fabricating thin-walled structures and maintaining process stability. Previous research on direct metal laser sintered (DMLS) thin-walled components indicates that achieving consistent mechanical properties is challenging due to localized heat accumulation and variable cooling rates in thin sections. Specifically, studies on thin-walled maraging steel (MS1) demonstrate that tensile strength is strongly influenced by wall thickness and may differ significantly from values observed in solid models [Bochnia 2023]. Furthermore, achieving precise geometric control and stable layer height in directed energy deposition (DED) requires a thorough understanding of how deposition parameters, such as laser power and travel speed, influence melt pool dynamics. While dimensional analysis has been utilized in powder-based direct metal deposition (DMD) to predict layer thickness and process stability [Kumar 2013], wire-based systems offer greater suitability for industrial applications due to higher deposition efficiency and reduced oxidation risk. Nevertheless, wire-based systems present distinct challenges in controlling the interfacial transition zone and regulating elemental mixing between dissimilar alloys. Steel-based hybrid systems frequently integrate austenitic stainless steels, such as 316L, with low-alloy or mild steels, such as ER70-S, to optimize both performance and cost. These properties are important in energy and petrochemical industries for components such as pressure vessels and heat exchangers, where it requires the combination of high corrosion resistance of stainless steel and good structural efficiency of mild steel.

316L stainless steel is an austenitic grade steel that is recognized for good weldability and corrosion resistance [Zhong 2017]. During DED processes, it generally solidifies into a columnar dendritic microstructure aligned with the thermal gradient. The pre-dominant phase is austenite, accompanied by varying amounts of δ -ferrite. Wire DED can typically produce

higher ferrite content compared to powder DED, attributable to differences in cooling rates [Das 2023]. ER70-S mild steel is widely used in WAAM due to its good structural efficiency and consistent mechanical properties [Tenuta 2021]. Its microstructure is highly responsive to the thermal cycle and cooling rates. Regions distant from heat sources are generally in the form of polygonal ferrite and pearlite grains, whereas areas nearer to heat source may develop acicular ferrite and bainite. Higher deposition speeds have been shown to refine grain size and substantially decrease pore and crack formation [Dekis 2025].

Recent studies show the research on joining of AISI 410 stainless steel with AWS ER70-S mild steel, and the optimization of combining AISI 316 stainless steel along with AISI 1008 mild steel [Tenuta 2021], [Ogbonna 2023]. Additional research on functionally graded materials (FGMs) shows producing dissimilar steels to evaluate their fatigue limits and fatigue crack growth. Most steels printed using DED systems achieved robust metallurgical bonds without defects such as fusion gaps or delamination [Liu 2014]. A transition zone develops where elements like chromium (Cr) redistribute in 316L/mild steel prints, the Cr concentration decreases from 10-12 wt% in the stainless-steel region to a steady state in the mild steel [Tenuta 2021]. Hardness varies across the transition region, with higher hardness in the stainless steel region than in the mild-steel region. Increased travel speed results in a faster cooling rate, leading to the formation of finer microstructures such as acicular ferrite, enhancing yield and tensile strength [Dekis 2025].

Although multi-material additive manufacturing has garnered increasing attention, limited research has focused on fabricating stainless steel and mild steel sandwich structures using wire-based DED. In particular, the interaction between 316L stainless steel and ER70-S mild steel at their interface, especially in terms of microstructure and mechanical behavior, remains underexplored. Investigating the bonding mechanisms between these dissimilar materials is crucial, as elemental diffusion and phase transformations can significantly influence bond quality and local mechanical properties. This research therefore focuses on addressing this gap by investigating how the microstructure and hardness change in a 316L stainless steel and ER70-S mild steel sandwich structure fabricated with the Meltio M600 laser-wire DED system. The study examines how the materials bond and transition at the interface using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), electron backscatter diffraction (EBSD), and Vickers microhardness (HV0.1) tests. The findings are intended to help us understand how well these two steels work together and how they perform mechanically when processed with wire-based DED.

2 MATERIALS AND METHODOLOGY

2.1 Materials

Both wires were supplied with BS300 spools with a nominal diameter of 1.0 mm and a spool weight of 15 kg, as specified in the supplier data sheets. Meltio's datasheet lists the nominal chemical composition in Table 1.

Chemical Element	Stainless Steel (316L)	Mild Steel (ER 70-S)
Carbon (C)	0.02	0.07
Silicon (Si)	0.9	0.85
Manganese (Mn)	1.7	1.45

Chromium (Cr)	18.5	-
Sulphur (S)	-	0.02
Phosphorus (P)	-	0.01
Nickel (Ni)	12.0	-
Molybdenum (Mo)	2.7	-
Iron (Fe)	Bal.	Bal.

Table 1. Chemical Composition of Meltio Stainless Steel 316L and Mild Steel ER70-S (wt.%).

2.1.1 Stainless Steel 316L

Meltio 316L wire is classified as (ER316LSi / G 19 12 3 L Si / 1.4430). The melting point is 1398 °C and the wire density is 8.0 g/cm³. According to the datasheet, the as-printed microstructure is mainly austenitic (FCC) with some ferritic content, which can be reduced by heat treatment if needed. Meltio reports typical mechanical properties including a yield strength of approximately 470 MPa, an ultimate tensile strength near 590 MPa, and an elongation of around 37%. These values demonstrate a combination of strength and ductility that is suitable for structural and corrosion-resistant applications.

2.1.2 Mild Steel ER70-S

Meltio mild steel wire is classified as (ER70-S / S 42 4 M21 3Si1 / AWS A5.18). The melting temperature range is 1425 to 1485 °C and the wire density is 7.8 g/cm³. The datasheet states that the as-printed microstructure has a ferritic matrix with pearlitic regions. This material typically has a yield strength of about 420 MPa, an ultimate tensile strength near 500 MPa, and an elongation at break of around 22%. These properties show a good balance of strength and ductility, which is common for ER70-S welding-grade steels. As a result, this alloy works well for structural uses where moderate strength and good weldability are important.

2.2 Methodology

All samples were printed using the Meltio M600 laser-based Wire-Directed Energy Deposition (W-DED) system. This setup uses multiple lasers to create a melt pool while continuously feeding in metallic wire, with argon gas flowing throughout to prevent oxidation.

For this study, exactly one sample was printed for each of the following three criteria:

- S1: A solid, 15-layer specimen made entirely of 316L stainless steel.
- S2: A solid, 15-layer specimen made entirely of ER70-S mild steel
- S3: A 30-layer "sandwich" structure, created by printing 15 layers of 316L stainless steel followed immediately by 15 layers of ER70-S mild steel.

The printing parameters were kept the same across all three prints. The laser power was locked in at 1000 W, and the argon flow rate was maintained at 15 L/min. For the wire feed rates, 316L was fed at 540 mm/min and ER70-S at 600 mm/min. Every layer was laid down sequentially, keeping the material composition completely consistent within each individual layer.

Solid specimens were fabricated with nominal dimensions of 45 × 15 × 15 mm³, and the sandwich specimen measured 45 × 15 × 30 mm³. Deposition was carried out layer by layer, with no graded compositional transitions between materials.

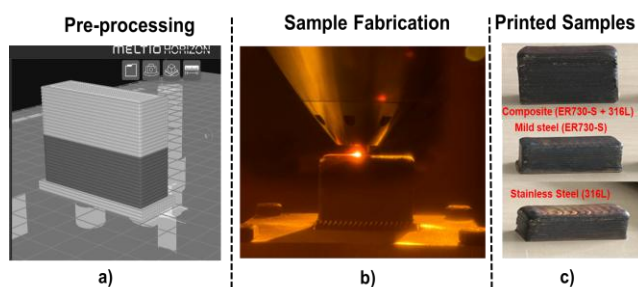


Figure 1. Fabrication workflow of the multi-material samples produced by wire-based Directed Energy Deposition: a) digital slicing and pre-processing of the sandwich structure model using the Meltio Horizon software environment; b) in-situ deposition process during fabrication on the Meltio M600 system; c) final printed specimens.

2.3 Microstructural Characterization

Scanning Electron Microscopy (SEM) was performed on cross-sections to examine melt pool shape, grain structure, and the boundary between 316L stainless steel and ER70-S mild steel. Energy-Dispersive X-ray Spectroscopy (EDS) was conducted at the interface to analyze elemental distribution. Line scans and elemental maps identified changes in chromium, nickel, and iron across the transition. Electron Backscatter Diffraction (EBSD) was carried out in selected areas to determine phase composition and crystal orientation. Phase maps confirmed FCC austenite in the 316L region and BCC ferrite in the ER70-S region.

2.4 Hardness

Microhardness measurements were conducted on the cross-section to evaluate the mechanical response across the deposited sandwich structure. Vickers microhardness testing utilized a load of HV0.1, corresponding to approximately 0.1 kgf (≈ 0.98 N). Measurements were obtained across the sample cross-section to demonstrate hardness variation in the mild steel, interface, and stainless-steel regions.

Figure 2(a) shows an initial hardness map along the build direction, with indentations spaced 0.5 mm apart to give an overview of hardness changes across the structure. To precisely study the interface region, additional measurements were taken at 0.1 mm intervals, as shown in Figure 2(b). The lesser distance allowed observation of hardness changes in the transition zone between the two materials. This approach helped identify local mechanical differences caused by microstructural changes and elemental migration near the stainless steel-mild steel interface.

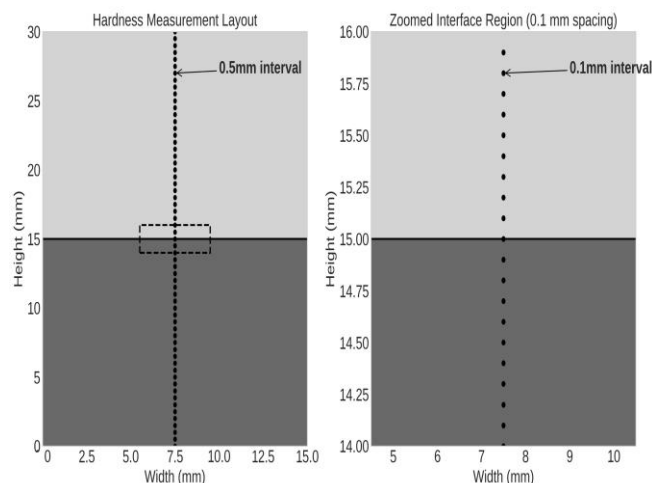


Figure 2. Schematic representation of the Vickers microhardness measurement locations across the deposited structure: a) overview hardness mapping with 0.5 mm indentation spacing across the sample

height; b) detailed hardness measurements near the interface region with 0.1 mm spacing to capture localized hardness variations.

3 RESULTS AND DISCUSSION

3.1 Optical Microscopy

Optical microscopy was used to examine the surface and printed texture of monolithic and sandwich samples made from 316L stainless steel and ER70-S mild steel. The images show the printing tracks created during the deposition process. Bead boundaries and overlapping melt-pool tracks on the surface are visible, highlighting the sequence in which the material was added. Both materials show consistent bead shapes and continuous tracks, suggesting stable conditions during fabrication. The surface features also exhibit the typical roughness found in additively manufactured metal parts, resulting from the rapid melting and solidification of the wire feedstock.

In sandwich samples, optical microscopy clearly shows the layered structure (see Figure. 3). The boundary between the two materials is easy to differentiate because of the minor differences in surface texture and layers deposition. The images (Figure 3) show that the deposition tracks extend across the interface, suggesting that the materials are well-bonded. There are some small differences in bead shape between the layers, likely due to differences in the two alloys' thermal properties, but no large defects, such as delamination or incomplete fusion, were found during the optical examination. The structural integrity of the deposition was formally classified by evaluating the tracks and interface according to the ISO/ASTM DIS 52969 standard for defect classification in metallic additive manufacturing. Optical examinations confirmed the complete absence of large macro-defects, such as delamination or incomplete fusion, indicating that the metallurgical bond meets the stringent requirements of Quality Level B. Additionally, the presence of continuous deposition tracks and stable bead shapes demonstrates that the process conditions remained highly stable, thereby preventing the formation of critical structural flaws across the dissimilar metal interface.

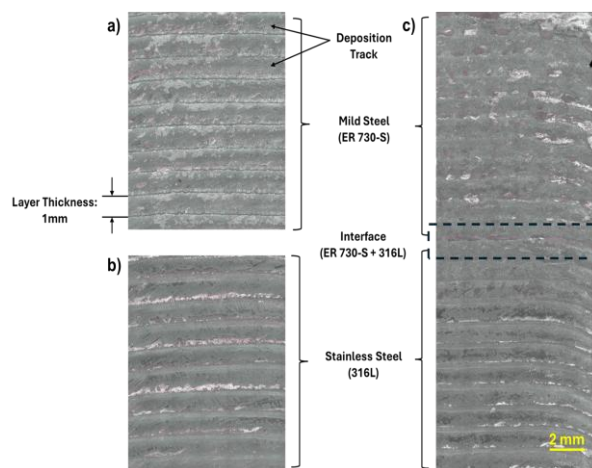


Figure 3. Optical microscopy images of the printed samples showing the layered morphology produced by wire-based Directed Energy Deposition: a) ER70-S mild steel, b) 316L stainless steel; c) transition region of the multi-material structure highlighting the interface between ER70-S mild steel and 316L stainless steel.

3.2 SEM Microstructural Analysis

Scanning Electron Microscopy (SEM) was used to study the microstructure of the sample in detail. SEM images (see Figure 4) revealed clear differences between the ER70-S mild steel and 316L stainless steel areas, showing how the composition and

thermal history affect the deposition process. In the ER70-S region, the microstructure is formed of ferritic grains with some lamellar pearlite colonies. At lower magnification (Figure 4), the ferritic grains appear roughly equal in size and are spread evenly across the layer. Lamellar pearlite structures are visible in certain grain areas, which is typical for ER70-S under given process conditions. These results match the expected ferrite–pearlite microstructure often seen in ER70-S steel after rapid thermal cycles. Similar ferrite–pearlite structures have been reported in additively manufactured steel systems, where rapid thermal cycling promotes the formation of ferritic matrices with localized pearlite colonies within the deposited layers [Chumaevskii 2023].

At higher magnification, more microstructural details become visible (Figure 4). The pearlite areas show clear lamellar patterns. These features are likely due to rapid solidification and repeated heating and cooling during layer-by-layer deposition. In comparison, the 316L stainless steel region is mostly austenitic, with smooth interiors and clear grain boundaries. This observation is consistent with previous studies on additively manufactured 316L stainless steel, where the material predominantly solidifies as austenite due to its nickel-rich composition [Riffel 2026], [Kruzel 2016]. These austenitic grains are larger and more continuous than the ferritic grains in the mild steel. In addition to the observations in the mild steel and stainless-steel areas, a transitional zone is visible at the interface between the two materials. In the transition region, several single-phase grains are observed surrounded by lath type structure. The grains here are less uniform than in the individual materials, and there is noticeable microstructural refinement. This transition likely occurs due to mixing of the molten materials and the diffusion of alloying elements during deposition. This difference comes from the alloys' different crystal structures: 316L stainless steel mainly forms face-centred cubic (FCC) austenite, while ER70-S mild steel forms body-centred cubic (BCC) ferrite. Overall, the SEM results show that several microstructural phases coexist in the deposited material and highlight how changes in alloy composition and temperature affect the microstructure during DED.

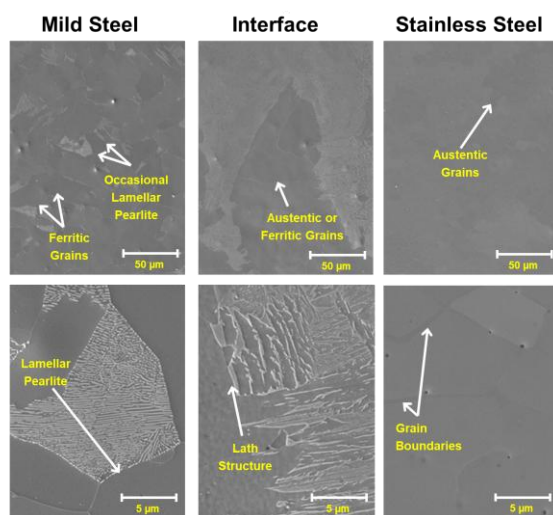


Figure 4. SEM micrographs showing microstructural features observed in different regions of the printed samples First row with print magnification of 1000x and second row with print magnification of 10000x.

3.3 Energy Dispersive Spectroscopy (EDS) Analysis

Energy-dispersive spectroscopy (EDS) was used to analyze the elemental distribution at the interface between 316L stainless steel and ER70-S mild steel. The black dashed box marks the transition zone where the elemental composition changes

between the two materials (Figure 5). The intensity profiles show a clear gradient across the interface. Chromium, nickel, and molybdenum, which are typical of 316L stainless steel, are more intense on the stainless-steel side and decrease toward the mild steel. In contrast, iron and manganese intensities rise toward the ER70-S side. The transition begins as a sharp step from 316L material, followed by a more gradual region. However, the transition in the element's changes within the thickness of one deposition layer (800 µm).

For better understanding, surface EDS was conducted in the transitional region shown in Figure 5. The highlighted box represents the area of the entire interface where the elemental distribution was captured. Surface EDS mapping, shown in Figure 5, was used to examine the distribution of elements at the interface. The close-up image highlights the point where the two materials meet, and the dashed box marks the area selected for detailed mapping. The combined elemental map shows a clear difference in composition between stainless steel and mild steel areas. The individual maps show that chromium and nickel are mostly found in stainless steel, while iron is the main element throughout the structure. Manganese appears mainly in the mild steel, matching the typical composition of ER70-S. The maps show that the interface is a narrow region where elements from both materials mix, rather than having a clear boundary. This suggests that mixing occurred in the melt pool during deposition, allowing certain alloying elements to diffuse across the interface. Such elemental redistribution is typical in multi-material additive manufacturing processes, where the melt pool convection and repeated thermal cycles promote interdiffusion of alloying elements across the interface, resulting in gradual compositional transitions between dissimilar materials [DeNonno 2024]. As a result, the elements are redistributed, helping to form a metallurgical bond between the two materials. This creates a gradual change in microstructure and mechanical properties throughout the sandwich structure.

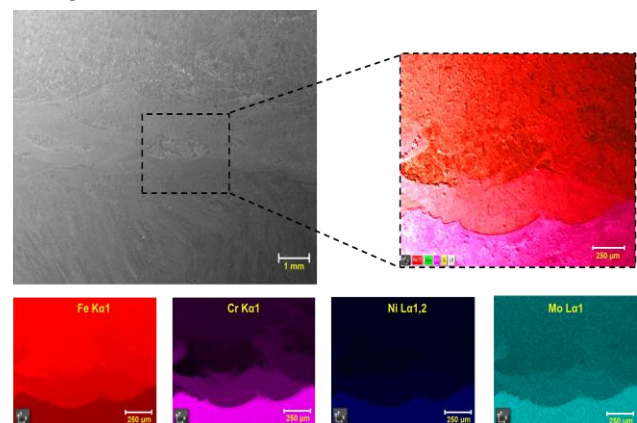


Figure 5. EDS analysis of the stainless steel–mild steel interface, Surface EDS of the interface region, illustrating the localized area of elemental redistribution.

3.4 Interfacial Microstructure and Elemental Redistribution

Electron Backscatter Diffraction (EBSD) analysis was used to study the crystal orientation and grain morphologies at the interface between ER70-S mild steel and 316L stainless steel. The band-contrast maps in Figure 6 illustrate how the microstructure changes across the mild steel, the interface, and the stainless-steel regions. In the mild steel area, the microstructure has fine, irregularly shaped grains, which match the ferritic structure seen earlier in the scanning electron microscopy (SEM) analysis (Figure 4). The band-contrast image shows a mix of grain structures, likely caused by rapid

solidification and repeated heating and cooling during the wire-based L-DED process.

Approaching the interface region, a distinct transition in grain morphology is evident. The maps show a mix of grain structures in this area, reflecting the effects of compositional changes and heat on the two materials. The interface shows irregular grain boundaries and areas with smaller grains, suggesting that the molten material was partially mixed during deposition. In comparison, the stainless-steel region has larger grains, which match the austenitic structure of 316L stainless steel. Electron backscatter diffraction (EBSD) phase and band-contrast maps indicate the formation of a distinct transitional layer between the two base materials. Within this region, features characteristic of a martensite-like lath morphology are present in the body-centered cubic (BCC) phase. This interpretation is further supported by energy-dispersive X-ray spectroscopy (EDS) analysis (Figure 5), which shows that the lath-structured zone corresponds to an area with intermediate chromium (Cr) and nickel (Ni) concentrations. The diffusion of these hardenability-enhancing elements from 316L stainless steel into the ER70-S melt pool, combined with the rapid cooling rates characteristic of the wire-directed energy deposition (wire-DED) process, establishes localized thermodynamic conditions that inhibit pearlite formation and favor martensitic transformation. Therefore, the presence of lath martensite in this region is strongly supported.

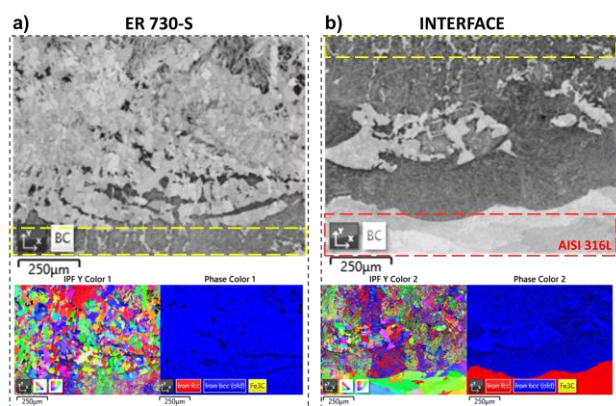


Figure 6. EBSD contrast maps showing microstructural variation across the deposited structure: a) mild steel ER 70-S region and the transition toward the interface; b) interface region and marked bottom AISI 316L stainless-steel region.

3.5 Hardness Distribution Across the Sandwich Structure

Figure 7 shows the microhardness distribution across the sandwich structure. Measurements were initially conducted at 0.5 mm intervals to obtain an overall hardness profile across the sample.

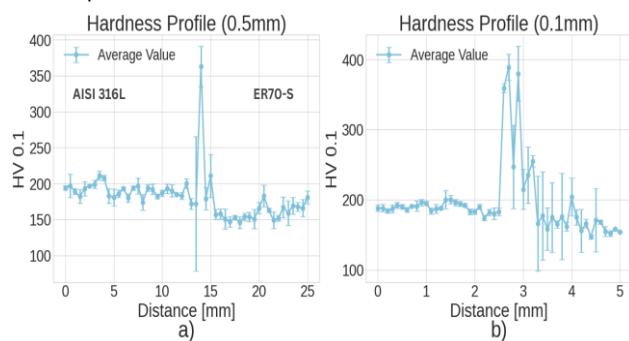


Figure 7. Vickers microhardness distribution across the stainless steel–mild steel sandwich structure: a) hardness profile measured with 0.5 mm indentation spacing; b) detailed hardness measurements with 0.1 mm spacing near the interface region.

Quantitative analysis of hardness profiles (Figure 7) identifies distinct mechanical zones within the sandwich structure. In the monolithic regions, hardness values remain relatively stable. The 316L stainless steel region demonstrates a mean hardness of 191.5 ± 8.4 HV 0.1. The ER70-S mild steel region exhibits a lower mean hardness of 162.6 ± 12.8 HV 0.1. The greater standard deviation in the mild steel is attributed to the heterogeneous distribution of lamellar pearlite colonies within the softer ferritic matrix. The transition zone is the region where hardness values deviate from the stable base averages of the two monolithic materials. It is clearly shown in the 0.1 mm resolution profile (Figure 7b). Hardness values increase sharply at 2.6 mm and gradually return to near-base levels at about 3.5 mm, resulting in a transition-zone width of 0.9 mm (900 µm), which matches the thickness of a single deposition layer. In this narrow interfacial region, the mean peak hardness is 387.3 ± 18.6 HV 0.1, and individual maxima reach 405 HV 0.1. This increase, over 100% greater than the base materials, is tied directly to microstructural phase changes and material mixing during deposition.

The hardness changes correlate well with EBSD results, as when approaching the transition from the 316L side, the increase to maximal hardness is sharp, which corresponds to a sharp transition to austenite seen in Figure 6b. Approach to maximal hardness from the ER730-S side is more gradual, as it corresponds to the increasing amount of lathe structure.

4 CONCLUSION

This study investigated the microstructure and hardness of a sandwich structure made from 316L stainless steel and ER70-S mild steel, using a laser-based wire Directed Energy Deposition (DED) process. Optical and electron microscopy showed that both materials formed stable beads and continuous layers. SEM analysis found that the mild steel area mostly had ferritic grains with lamellar pearlite, while the stainless-steel area was mainly austenitic. At the interface, a transitional microstructure appears to be linked to the diffusion of chromium. EBSD confirmed the formation of a transitional area with a structure different from both base materials, indicating metallurgical bonding through a transition zone rather than a sharp boundary.

EDS analysis showed that alloying elements diffused across the interface. Chromium and nickel spread from the stainless-steel side into the mild steel. Microhardness tests showed that each material had a stable hardness, but a clear hardness peak was observed at their interface. Detailed measurements indicated that the transition zone was relatively narrow and aligned with localized changes in microstructure and elemental distribution. The sharp increase in hardness in this region, peaking at approximately 380 HV0.1, provides additional mechanical evidence for the presence of a hard phase such as lath martensite. This localized hardening is consistent with microstructural observations from electron backscatter diffraction (EBSD) and the chromium/nickel (Cr/Ni) gradients identified by energy-dispersive X-ray spectroscopy (EDS). These findings indicate that elemental interdiffusion across the melt pool has significantly altered the local phase transformation behavior.

This study demonstrates that Wire-DED produces a defect-free 316L/ER70-S bond meeting ISO/ASTM DIS 52969 standards. However, a critical technological limitation is the unavoidable formation of a brittle, martensite-like interfacial phase driven by the process's rapid cooling. This creates a sharp transition zone where hardness spikes to 387.3 ± 18.6 HV 0.1, doubling the base values of 316L (191.5 ± 8.4) and ER70-S (162.6 ± 12.8).

While structurally sound, this hardened interface acts as a stress concentrator, remaining a primary limitation for components subjected to dynamic loading.

5 DIRECTION OF FUTURE RESEARCH

Further research is required to advance the understanding and application of multi-material structures. Future investigations should include tensile and fatigue testing of sandwich structures to assess their strength and ductility. Investigations should also address how variations in process parameters, including laser power, layer thickness, and wire feed rates, influence the printed structure, particularly the transition zone, shape stability, and microstructure, with the aim of minimizing hardness differences at the interface. Additionally, evaluating the wire-based directed energy deposition (DED) process on complex, thin-walled geometries is necessary to determine process controllability and the consistency of mechanical properties in non-linear multi-material structures.

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