

Tensile Testing and Fracture Behaviour of 17-4 PH Stainless Steel Produced by Atomic Diffusion Additive Manufacturing Using a Modified Specimen Geometry

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Abstract:

This study investigates a compact tensile-specimen geometry with enlarged, shoulder-mounted gripping heads for 17-4 PH stainless steel produced by Atomic Diffusion Additive Manufacturing (ADAM). The geometry was designed to reduce material consumption while providing stable gripping and promoting fracture localization within the gauge section. Specimens with a 20 mm gauge length and 6 mm gauge diameter were manufactured horizontally using a Markforged Metal X system and subsequently debound and sintered. Tensile testing was performed based on ASTM E8/E8M using three specimens. All specimens fractured within the gauge section without slippage or grip-related failure. The mean ultimate tensile strength was 1194.22 ± 4.53 MPa, the mean 0.2% proof strength was 837.49 ± 4.24 MPa, and the mean elongation at fracture was $2.96 \pm 0.34\%$. Fractographic analysis revealed predominantly planar fracture surfaces, inter-bead voids, and interlayer discontinuities, while ductile dimple morphology was observed at the microscale. The results indicate that the proposed geometry provided stable gripping and consistent fracture localization under the investigated conditions and may represent a practical compact specimen-design approach for tensile testing of ADAM-produced metallic materials.

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1. INTRODUCTION

Metal additive manufacturing (AM) enables the production of metallic components directly from digital models through layer-by-layer material deposition. Several process categories are used for metallic materials, including Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Binder Jetting (BJ), and Material Extrusion (MEX). These processes differ in their material deposition mechanisms, thermal histories, and post-processing requirements, which can significantly influence the

resulting microstructure and mechanical properties [1–4].

ADAM is a commercial metal MEX process in which a filament containing metal powder and a polymer binder is deposited layer-by-layer to form a green part. The polymer binder is subsequently removed, and the remaining metal powder is consolidated during sintering [5, 6]. In contrast to fusion-based AM processes, the final properties of ADAM components are therefore influenced not only by the deposition process but also by

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debinding, sintering, densification, and the resulting interlayer and interfilament bonding.

17-4 PH stainless steel is an attractive material for metal AM because of its high strength, hardness, and corrosion resistance. Previous studies [7–11] have demonstrated that 17-4 PH components produced by metal MEX and ADAM can achieve substantial tensile strength, while their mechanical properties are influenced by build orientation, processing conditions, microstructure, porosity, surface condition, and post-processing. Studies of 17-4 PH produced using the Markforged Metal X system have reported a predominantly martensitic microstructure together with patterned voids associated with incomplete bonding between adjacent deposited filaments [9]. Such manufacturing-induced features can affect the mechanical integrity and fracture behaviour of the material. In addition, variations in build orientation, machining, surface finish, and heat treatment have been shown to produce significant changes in the tensile properties of ADAM-produced 17-4 PH stainless steel [8, 10, 11].

Tensile testing is one of the fundamental methods used to determine the mechanical properties of metallic materials. Standardized tensile tests commonly employ specimens with defined gripping and gauge sections, with ASTM E8/E8M providing requirements for tensile testing of metallic materials and standardized specimen dimensions [12]. The use of a reduced gauge section is intended to provide a defined region in which tensile deformation and fracture can be evaluated. However, the measured tensile response is not necessarily independent of specimen geometry. Experimental investigations of additively manufactured materials have demonstrated that different tensile specimen geometries can produce differences in the measured mechanical response, indicating that specimen geometry should be considered when interpreting tensile-test results [13].

The interaction between specimen geometry and gripping conditions is also important. The transition between the gripping and gauge regions can influence the local stress state and deformation behaviour, while the gripping configuration determines how the applied tensile force is transferred into the specimen. Recent experimental and numerical work has shown that specimen geometry and gripping system can affect stress distribution, stress triaxiality, ductility, and fracture location [14]. These effects are particularly relevant for high-strength metallic materials exhibiting

limited plastic deformation, because a large tensile load may need to be transferred through relatively small gripping regions before significant plastic deformation occurs.

For a specimen used in tensile testing, insufficient mechanical engagement between the specimen and grips may result in slippage or unstable load transfer. Such behaviour can affect the measured force–displacement response and reduce the repeatability of the tensile test. Conversely, an unfavourable transition between the gripping and gauge regions can promote local stress concentrations and premature fracture outside the intended gauge section. This issue is not limited to conventional metallic specimens; material-extrusion AM specimens may additionally contain geometrical features originating from the deposition process that act as stress concentrators and can influence fracture location [15]. Therefore, specimen geometry, surface condition, manufacturing-induced features, and gripping configuration should be considered together when designing tensile tests for material-extrusion AM components.

Specimen size is another practical consideration for additively manufactured materials. Materials with high strength and limited elongation may fracture after relatively small plastic deformation, reducing the experimental benefit of unnecessarily long gauge sections. In addition, the production of tensile specimens by AM requires material, printing time, debinding, and sintering resources. A compact specimen geometry can therefore provide practical advantages by reducing specimen volume and manufacturing requirements, provided that the geometry maintains stable load transfer and promotes fracture within the intended gauge section. The use of a compact geometry should nevertheless be considered as a specimen-design choice rather than an assumption that smaller specimens inherently provide more accurate material properties.

Although the mechanical properties of 17-4 PH stainless steel produced by ADAM have been investigated in several studies, previous research [7–11] has mainly focused on build orientation, deposition strategy, microstructure, porosity, surface condition, heat treatment, and general mechanical performance. Comparatively less attention has been given to the development and experimental evaluation of compact tensile-specimen geometries specifically adapted to high-strength, low-ductility metal material-extrusion components. Existing research has demonstrated

that specimen geometry can influence tensile-test results [13], while the combined effects of specimen geometry and gripping configuration can influence stress distribution and fracture behaviour [14]. However, the use of a compact specimen geometry with enlarged, shoulder-mounted gripping heads for ADAM-produced 17-4 PH stainless steel, intended to reduce specimen material consumption while maintaining stable gripping and fracture localization within the gauge section, has not been sufficiently investigated. The present study therefore addresses the specimen-design and testing aspects of ADAM-fabricated metallic materials rather than proposing a modification of the ADAM manufacturing process itself.

Therefore, the present study proposes and experimentally evaluates a compact tensile-specimen geometry with enlarged, shoulder-mounted gripping heads for 17-4 PH stainless steel produced by ADAM. The geometry was developed with two practical objectives: (i) to provide stable mechanical engagement with the tensile grips and promote fracture localization within the gauge section, and (ii) to reduce specimen volume and associated material consumption compared with larger conventional tensile-specimen configurations. The proposed geometry is intended as a specimen-design approach for tensile testing of high-strength, low-ductility metallic materials produced by material-extrusion additive manufacturing. It is not intended to modify or replace the requirements of standardized tensile testing, and its applicability should be assessed under the specific material, manufacturing, and testing conditions considered.

The objective of this study was to experimentally evaluate the proposed specimen geometry using ADAM-produced 17-4 PH stainless steel. Particular attention was given to gripping stability, specimen slippage, fracture localization, repeatability of the tensile response, and the relationship between the measured mechanical properties and the fracture morphology observed by scanning electron microscopy (SEM).

2. MATERIALS AND METHODS

For the printing process, 17-4 PH stainless steel was selected due to its high strength and corrosion resistance. The tensile specimens were manufactured at the Department of Machining and Manufacturing Technology, University of Žilina, Slovakia, using a Markforged Metal X system. In the ADAM process, the feedstock material was supplied

as a composite filament consisting of fine metallic powder encapsulated within a thermoplastic binder matrix. The chemical composition specified by the manufacturer for the 17-4 PH stainless steel feedstock is presented in Table 1 [16].

Table 1. Chemical composition of 17-4 PH stainless steel provided by the manufacturer [16]

Elements	[wt. %]
C	0.07 max
Cr	15-17.5
Ni	3-5
Cu	3-5
Nb	0.15-0.45
Mn	1.0 max
Si	1.0 max
P	0.04 max
S	0.03 max
Fe	Bal.

Tensile specimens with enlarged, stepped heads were used to improve mechanical fixation within the testing machine grips and to reduce the risk of specimen slippage. Proper specimen-grip engagement and alignment are important considerations in tensile testing, as inadequate fixation may affect load transfer and lead to slippage or premature failure in the gripping region [17, 18]. In particular, challenges related to tensile-grip-to-specimen alignment and specimen engagement have been reported for additively manufactured 17-4 PH stainless steel specimens [18]. Therefore, enlarged, shoulder-mounted heads were adopted in the present study to provide more secure mechanical fixation and facilitate load transfer to the gauge section.

In the final tensile tests, all three specimens fractured within the gauge section, and no grip-related failure was observed. This observation indicated that the modified specimen geometry provided adequate fixation under the applied testing conditions.

To reduce material consumption and printing time, a modified specimen geometry with an effective gauge length of 20 mm was adopted. The gauge diameter was maintained at 6 mm, corresponding to an initial cross-sectional area of 28.27 mm², while reducing the amount of material required for specimen fabrication (Fig. 1).

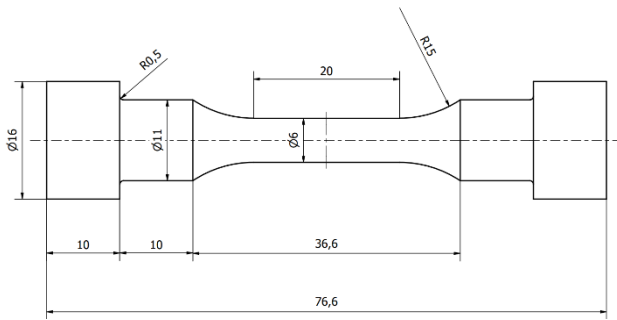


Fig. 1. Schematic representation of the modified tensile specimen

The main dimensional differences between the original and modified specimen geometries are summarized in Table 2, with the modifications primarily involving a reduction in the gripping, transition, and gauge-section lengths while maintaining the same head and gauge diameters.

Table 2. Comparison of the original and modified tensile-specimen geometries

Parameter	Original specimen	Modified specimen	Difference
Head diameter	16 mm	16 mm	0
Head length, each side	20 mm	10 mm	-10 mm
Transition diameter	11 mm	11 mm	0
Transition length, each side	19 mm	10 mm	-9 mm
Gauge diameter	6 mm	6 mm	0
Gauge length	70 mm	20 mm	-50 mm
Overall length	148 mm	76.6 mm	-71.4 mm
Overall length reduction	—	—	48.2%

The specimen was fabricated in a horizontal (lying) orientation to minimize support entrapment and ensure the quality of the final component (Fig. 2).

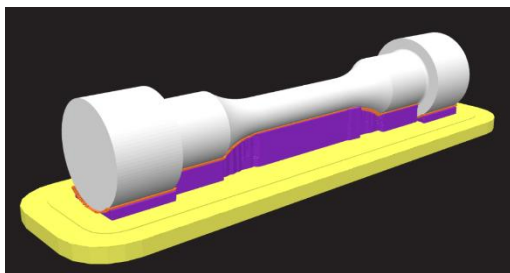


Fig. 2. Horizontal orientation of the specimen

The specimens were fabricated with a layer height of 0.127 mm, a 100% solid infill, and four perimeters. The total fabrication time for the green part was approximately five hours. To ensure structural stability during fabrication, the specimens were oriented horizontally and supported using dedicated support structures. A ceramic release layer was applied between the specimen and its supports to facilitate separation after sintering. Prior to fabrication, process simulation and layer-by-layer visualization were performed using the slicing software to verify the specimen geometry, orientation, and deposition sequence.

Following the AM stage, the green specimens were subjected to solvent debinding in a Wash-1 fluid unit using Opteon SF79 for 24 h. This process removed the primary binder and produced the porous brown state required for subsequent thermal consolidation.

The debound specimens were subsequently sintered in a Sinter-2 tube furnace under a controlled reducing atmosphere consisting of 97% Ar and 3% H₂, with a constant gas flow rate of 5 L/min and a dew point of -40 °C. The thermal cycle lasted 17 h and consisted of a 4 h gradual heating stage, followed by an isothermal holding stage at a peak temperature of 1315 °C for 3 h. The cycle was completed by controlled cooling over 10 h. During sintering, atomic diffusion promoted bonding between the metallic particles and densification of the material.

Tensile tests were subsequently conducted based on ASTM E8/E8M using the modified specimen geometry described above. The specimens featured enlarged, shoulder-mounted heads to improve clamping stability and reduce the risk of specimen slippage (Fig. 3). Because the specimen geometry differed from the standard ASTM configuration, particularly through the use of a 20 mm gauge length and a 6 mm gauge diameter, the testing procedure was considered ASTM E8/E8M-based rather than fully compliant with the standard specimen dimensions. The gauge diameter was 6 mm, corresponding to an initial cross-sectional area of 28.27 mm². Testing was performed at the Department of Materials Engineering, University of Žilina, Slovakia, using an INSTRON universal testing machine equipped with specialized grips designed to interface with the modified specimen heads. Three specimens were tested under identical conditions (n = 3).

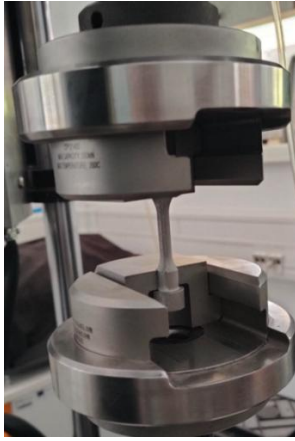


Fig. 3. Clamping of tensile specimen

3. RESULTS AND DISCUSSION

During the tensile tests, all three specimens fractured within the functional gauge section (Fig. 4). No specimen slippage or premature failure in the gripping regions was observed. The fracture locations indicate that the enlarged, shoulder-mounted gripping heads provided stable mechanical engagement and effective load transfer to the gauge section under the investigated testing conditions. The absence of grip-related failure is particularly relevant for the present specimen design because the main purpose of the enlarged heads was to prevent slippage and promote fracture within the reduced gauge section.



Fig. 4. Specimens after tensile testing

The tensile stress–strain response obtained from the three specimens is presented in Fig. 5. The mean maximum load was 33.78 ± 0.15 kN, corresponding to an ultimate tensile strength (R_m) of $1194.22 \pm$

4.53 MPa. The 0.2% proof strength ($R_{p0.2}$) was 837.49 ± 4.24 MPa, while the elongation at fracture (A) was $2.96 \pm 0.34\%$. The relatively small standard deviations indicate limited scatter in the measured tensile properties among the three tested specimens.

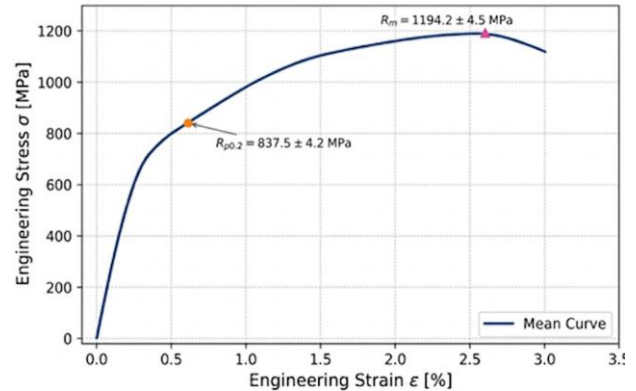


Fig. 5. Mean tensile curve and mechanical properties of 17-4PH steel

The individual results are given in Table 3. The maximum load and ultimate tensile strength showed particularly low variation, whereas the elongation exhibited somewhat greater scatter. This difference may be related to the sensitivity of fracture strain to local defects and microstructural variations. Importantly, all three specimens fractured within the gauge section, confirming consistent fracture localization for the investigated geometry.

The measured tensile properties are comparable with values reported for 17-4 PH stainless steel produced by material extrusion, although direct comparison should be made cautiously because of differences in feedstock, deposition parameters, build orientation, sintering conditions, specimen geometry, and post-processing [19–23]. Previous studies [20, 21] have demonstrated that processing parameters and heat treatment can substantially affect the strength and ductility of MEX-produced 17-4 PH. Therefore, the tensile properties obtained in the present study should be considered characteristic of the specific as-sintered material condition investigated here rather than representative of the maximum achievable properties of ADAM-produced 17-4 PH.

Table 3. Mechanical properties of 17-4 PH

Specimen ID	Fmax [kN]	Rm [MPa]	Rp0.2 [MPa]	A [%]
Specimen 1	33.63	1189.48	838.41	3.22
Specimen 2	33.78	1194.67	832.87	2.57
Specimen 3	33.92	1198.50	841.20	3.08
Mean ± SD	33.78 ± 0.15	1194.22 ± 4.53	837.49 ± 4.24	2.96 ± 0.34

The relatively high strength combined with limited elongation can be associated with the material condition and internal structure resulting from the selected manufacturing and sintering conditions. The specimens were manufactured horizontally and tested in the as-sintered condition without subsequent precipitation-hardening treatment. Previous studies [8, 20–24] have shown that build orientation, deposition parameters, sintering and post-processing can significantly influence the mechanical behaviour of MEX-produced 17-4 PH. Consequently, the measured properties cannot be attributed solely to the modified specimen geometry.

The present results also demonstrate the importance of the gripping configuration for the proposed compact specimen design. The approximately 48.2% reduction in overall specimen length was achieved while maintaining a 6 mm gauge diameter and 20 mm gauge length. Despite the reduced dimensions, all three specimens remained securely engaged during testing and fractured within the gauge section. This behaviour suggests that the enlarged, shoulder-mounted heads were effective in transferring the tensile load without inducing premature failure at the gripping regions. Previous studies [8, 13–15] have shown that specimen geometry, build orientation and gripping conditions can influence the measured mechanical response and fracture behaviour of additively manufactured materials. However, the present study specifically evaluates this combination of compact geometry and enlarged gripping heads for ADAM-produced 17-4 PH.

A macroscopic view of the fracture surface is presented in Fig. 6. The peripheral region clearly shows the outer contour layer (“shell”), characterized by a rough surface associated with partially sintered particles. The main fracture surface in the core/infill region is predominantly planar and approximately perpendicular to the loading direction. Pronounced necking was not observed, which is consistent with the relatively low elongation measured during tensile testing.

Higher-magnification examination of the subsurface region (Fig. 7) revealed secondary cracks approximately perpendicular to the main fracture surface. These cracks appear to follow interfaces between adjacent deposited strands or layers, indicating locally reduced cohesion between neighbouring deposited regions. Similar interlayer discontinuities have been reported for material-extrusion-produced 17-4 PH and have been

associated with deposition conditions, build orientation and sintering behaviour [19, 20, 22].

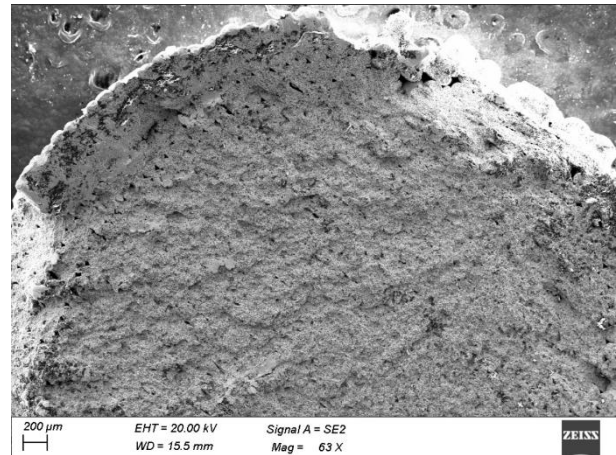


Fig. 6. Macroscopic view of the fracture and outer shell layer

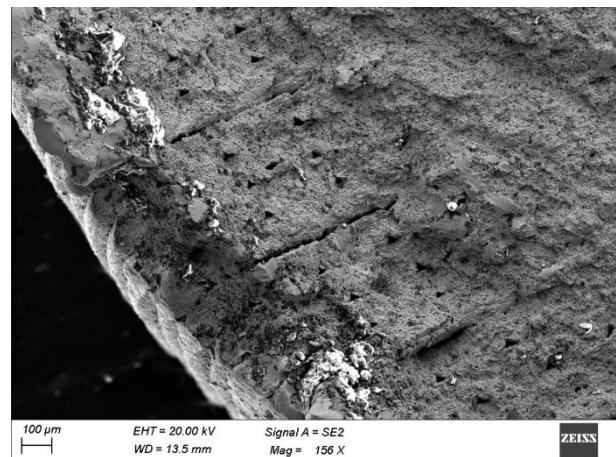


Fig. 7. Secondary interlayer delamination cracks near the surface

Inter-bead voids were also observed at the interfaces between adjacent deposited strands (Fig. 8). These voids exhibited relatively sharp and locally triangular geometries. Similar process-induced voids have been reported for MEX-produced 17-4 PH and have been related to deposition conditions, inter-bead bonding and subsequent sintering [19, 20, 22]. In the present study, these features are considered qualitative evidence of incomplete local bonding rather than a quantitative measure of total specimen porosity.

Quantitative image analysis of the fracture surfaces was not performed. Therefore, the observed voids cannot be used to determine the overall volumetric porosity or to quantify its contribution to the tensile properties. Their potential influence is discussed only in relation to the observed fracture morphology.

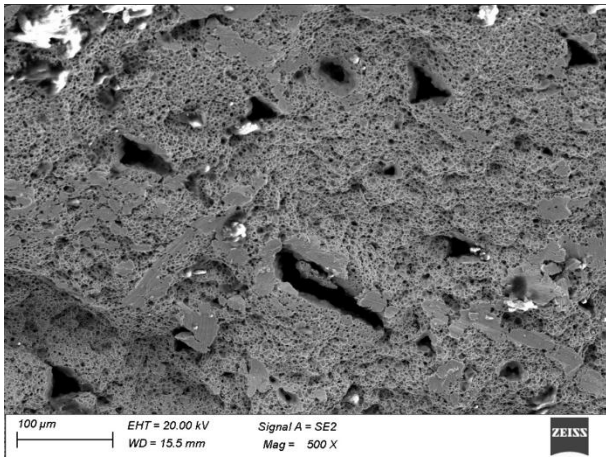


Fig. 8. Triangular inter-bead porosity at the strand interfaces

A higher-magnification image of a selected internal void is presented in Fig. 9. Cellular-to-dendritic-like features were observed on the inner surface of the void. These features may be associated with local material redistribution and microstructural evolution during high-temperature sintering. However, SEM observations alone do not allow the exact formation mechanism to be conclusively established. Therefore, the morphology is interpreted only as evidence of localized microstructural evolution rather than direct confirmation of a specific melting or solidification mechanism.

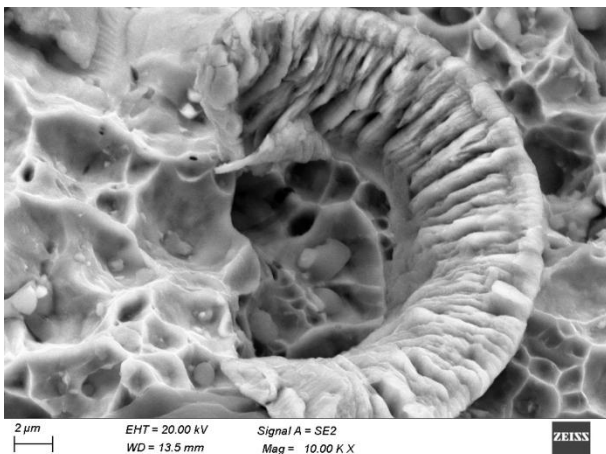


Fig. 9. Primary metallurgical void with a dendritic growth morphology on the inner wall

The observed fracture morphology provides a possible explanation for the combination of relatively high tensile strength and limited elongation. The metallic regions exhibited local ductile fracture characteristics, including fine dimple morphology, while inter-bead voids and interlayer discontinuities were present at several locations. Such discontinuities can act as local stress-concentration sites and preferential

locations for crack initiation and propagation. Consequently, they may contribute to the limited macroscopic plastic deformation observed in the specimens. This interpretation is consistent with previous studies [19–23] reporting relationships between internal defects, interlayer bonding, porosity and mechanical behaviour in MEX-produced 17-4 PH.

Recent CT-based investigations [25] have further demonstrated that manufacturing-induced defects can persist after processing and influence the mechanical behaviour of MEX-produced 17-4 PH. In contrast, the present investigation is based on fractographic observations and therefore does not provide three-dimensional quantification of internal defects. The present observations should consequently be regarded as qualitative evidence of defect-related fracture behaviour.

All specimens were manufactured in the horizontal orientation. Therefore, the observed fracture morphology represents the investigated horizontal-build configuration and cannot be directly generalized to other orientations. Previous studies [8, 20, 22] have demonstrated that build orientation can influence tensile strength, porosity and mechanical behaviour of MEX-produced 17-4 PH.

The principal contribution of this study is therefore the experimental evaluation of the proposed compact specimen geometry, rather than optimization of the ADAM manufacturing parameters. The geometry reduced the overall specimen length from 148 mm to 76.6 mm, corresponding to a reduction of approximately 48.2%. At the same time, all three specimens fractured within the gauge section without slippage or grip-related failure. These results demonstrate that the proposed geometry was functional under the investigated material and testing conditions.

However, the present study has several limitations. Only three specimens were tested; all specimens were produced in the horizontal orientation, and no direct experimental comparison with the original or standardized specimen geometry was performed. In addition, the tensile tests were conducted in the as-sintered condition using a specific gripping configuration. Therefore, the results should not be interpreted as a general validation of the geometry for all ADAM-produced materials. Further work should include a larger number of specimens and direct comparison with a conventional standardized geometry, as well as evaluation of different build orientations and material conditions.

4. CONCLUSION

This study investigated a compact tensile-specimen geometry with enlarged, shoulder-mounted gripping heads for 17-4 PH stainless steel produced by ADAM. The proposed geometry was designed to reduce specimen dimensions and material consumption while maintaining stable gripping and promoting fracture within the gauge section. Based on the investigated material, manufacturing conditions, and tensile-testing configuration, the following conclusions can be drawn:

- Specimen geometry and fracture localization: The modified specimen geometry provided stable mechanical engagement with the tensile-testing grips. All three specimens fractured within the gauge section, and no specimen slippage or premature failure in the gripping regions was observed. These results indicate that the enlarged, shoulder-mounted gripping heads were suitable for the investigated testing configuration.
- Mechanical properties: The three specimens exhibited low scatter in the measured tensile properties. The mean ultimate tensile strength was 1194.22 ± 4.53 MPa, the 0.2% proof strength was 837.49 ± 4.24 MPa, and the elongation at fracture was $2.96 \pm 0.34\%$. The relatively small standard deviations indicate consistent tensile behaviour among the tested specimens. However, the limited sample size ($n = 3$) should be considered when assessing the statistical repeatability of the results.
- Compact specimen design: Compared with the original specimen geometry, the modified design reduced the overall specimen length from 148 mm to 76.6 mm, corresponding to a reduction of approximately 48.2%. This reduction in specimen dimensions indicates the potential of the proposed geometry to decrease material consumption and manufacturing requirements. However, a direct quantitative comparison of material consumption with a standardized specimen geometry was not performed in the present study.
- Fracture behaviour: Fractographic analysis revealed predominantly planar fracture surfaces with limited macroscopic necking. Inter-bead voids and interlayer discontinuities were observed, while ductile dimple morphology was present at the microscale. These manufacturing-induced discontinuities may act as local stress-concentration sites and contribute to crack

initiation and propagation, which may help explain the combination of relatively high tensile strength and limited elongation observed in the tested specimens.

The results demonstrate that the proposed compact specimen geometry with enlarged, shoulder-mounted gripping heads can provide stable gripping and consistent fracture localization for tensile testing of ADAM-produced 17-4 PH stainless steel under the investigated conditions. The approximately 48.2% reduction in overall specimen length demonstrates the potential of the proposed design for reducing specimen dimensions and associated material and manufacturing requirements. Further studies involving a larger number of specimens, different build orientations and materials, and direct comparisons with standardized specimen geometries are required to further evaluate the broader applicability and repeatability of the proposed design.

The investigation was limited to 17-4 PH stainless steel produced by ADAM, a horizontal build orientation, the investigated specimen geometry, and three tensile specimens. The tensile tests were performed using a specific gripping and testing configuration based on ASTM E8/E8M. Therefore, the results cannot be directly generalized to other materials, build orientations, specimen geometries, gripping configurations, or AM processes.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DECLARATION OF AI USE

The authors declare the use of generative artificial intelligence (AI) and AI-assisted technologies in the preparation of this manuscript. Specifically, ChatGPT (version GPT-5.5, OpenAI) was used to improve the readability and language of the article. The AI tool was not used for data analysis, result interpretation, or drawing scientific conclusions. All content has been reviewed and verified by the authors to ensure accuracy and integrity.

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