

EFFECT OF HYDROGEN EMBRITTLEMENT ON MECHANICAL PROPERTIES OF ADDITIVELY MANUFACTURED 316L STAINLESS STEEL

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Abstract

Additive manufacturing (3D printing) represents a modern method of material production in many industrial sectors. Materials produced in this way can also be used in the field of hydrogen storage and transportation. This work deals with the influence of hydrogen on AISI 316L stainless steel produced by additive manufacturing using Selective Laser Melting (SLM) technology. Flat tensile test specimens were tested in the as-built condition after printing and after heat treatment. Recrystallization annealing was carried out in a vacuum furnace at a temperature of 1050 °C for 30 minutes, with a heating rate of 20 °C per minute, followed by furnace cooling. The specimens were then electrolytically hydrogen charged in 0.05 M sulfuric acid solution with the addition of KSCN at current densities 1 and 5 mA·cm⁻² for 8 hours. The effect of hydrogen on mechanical properties was evaluated by the slow strain rate tensile tests (SSRT). The presence of hydrogen slightly affected the tensile strength and ductility. The microstructure was also examined both in the as-built condition and after annealing. Annealing at 1050 °C resulted in recrystallization. The original layered structure with the presence of melt pools typical for materials produced by this way transformed into the common austenitic structure that can be observed in conventionally produced materials. Microhardness was also measured. In addition, fractographic analysis of the fracture surfaces was performed.

Keywords: Additive manufacturing, stainless steel, hydrogen embrittlement, slow strain rate test (SSRT)

1. INTRODUCTION

Hydrogen as a fuel has been discussed for many years. With the increasing global effort to reduce the consumption of fossil fuels, its utilization has gained significant attention. However, the use of hydrogen in the energy sector involves many challenges. A very serious problem is hydrogen embrittlement which leads to a degradation of mechanical properties such as ductility and strength, formation of microcracks, and subsequent material failure even at stresses below the ultimate tensile strength. Therefore, materials intended for hydrogen transport, storage, and energy applications must exhibit stable mechanical properties and sufficient resistance to hydrogen-induced degradation [1,2].

AISI 316L steel is an austenitic stainless steel characterized by high corrosion resistance and good mechanical properties. Due to its excellent resistance in aggressive environments containing acids, salts, and seawater, as well as its good performance at elevated temperatures, it is widely used in chemical, petrochemical, and energy industries, including pressure vessels, pipelines, and hydrogen storage systems. Its corrosion resistance is primarily attributed to alloying with molybdenum, and the steel exhibits relatively good resistance to hydrogen embrittlement, making it a suitable candidate for hydrogen-related applications [3,4].

Modern production methods of AISI 316L include additive manufacturing, particularly Selective Laser Melting (SLM). This technology uses metal powders that are selectively melted layer by layer using a high-energy laser, enabling the fabrication of complex geometries with high precision. However, SLM-produced materials typically exhibit a characteristic layered microstructure with melting pools, fine cellular substructure, and high

residual stresses, as well as process-related defects such as porosity and lack-of-fusion regions. These features significantly influence mechanical properties, hydrogen diffusion, and the susceptibility to hydrogen embrittlement [3-5]. Heat treatment can significantly modify the microstructure of SLM-produced materials. Recrystallization annealing leads to the removal of melt pools, reduction of residual stresses, and transformation of the original layered structure into a conventional austenitic microstructure like that of conventionally produced AISI 316L. These microstructure changes may affect hydrogen absorption, diffusion, and the overall mechanical response of the material in hydrogen environments [5-7].

The interaction between hydrogen and additively manufactured AISI 316L, particularly in different microstructural states, is still not fully understood and requires further investigation. The aim of this work is to evaluate the effect of hydrogen on the mechanical properties and microstructure of AISI 316L stainless steel produced by Selective Laser Melting in the as-built and annealed conditions using slow strain rate tensile testing (SSRT), microhardness measurements and fractographic analysis.

2. EXPERIMENTAL PART

2.1 Material description and microstructure

AISI 316L steel was prepared by SLM technology. The material was produced from gas-atomized powder supplied by Renishaw company, and its chemical composition is presented in **Table 1**. The specimens were printed in the form of flat tensile test samples. The samples were built in a vertical orientation, perpendicular to the build platform, not in a horizontal position.

Table 1 Chemical composition of atomized AISI 316L powder according to Renishaw certification [8]

Chemical Composition (wt %)										
C	Si	Mn	P	S	N	O	Cr	Mo	Ni	Fe
Max.	Max.	Max.	Max.	Max.	Max.	Max.	Min.-Max.	Min.-Max.	Min.-Max.	Balance
0.03	1.00	2.00	0.045	0.03	0.10	0.10	16.00-18.00	2.00-3.00	10.00-14.00	

Half of the specimens were left in the as-built condition after printing, while the remaining specimens were subjected to heat treatment. The heat treatment parameters were selected based on previous experiments performed on the same type of material according to [7]. Recrystallization annealing was performed in a vacuum furnace Classic under low vacuum conditions (500 Pa). The annealing temperature was 1050 °C with a holding time of 30 minutes and a heating rate of 20 °C per minute. Cooling was slow in the furnace chamber.

The annealing regime of 1050 °C for 30 minutes led to partial recrystallization and significant reduction in the presence of melt pools, which are typical for samples prepared by SLM technology. Cooling was very slow at low temperature gradient. Austenitic stainless steels are usually rapidly cooled from the austenitization temperature to prevent chromium carbide precipitation during cooling. However, due to the low carbon content of AISI 316L, no carbide precipitation was observed during slow cooling. Slow cooling also contributed to the elimination of residual stresses and prevented the formation of additional stresses during cooling.

Metallographic specimens were prepared and examined using an Olympus IX70 optical metallographic microscope in a direction perpendicular to the printing direction. The samples were polished and subsequently etched using V2 etchant. In the as-built condition, a typical texture of 3D-printed metals with melt pools was observed (**Figure 1a**), which were formed by melting individual powder particles. After annealing, the microstructure was partially recrystallized, most of the melting pools disappeared, and the structure became more like conventionally produced austenitic steel. However, local features related to the original SLM process were still present (**Figure 1b**), and complete recrystallization was not achieved as typical annealing twins were not fully developed.

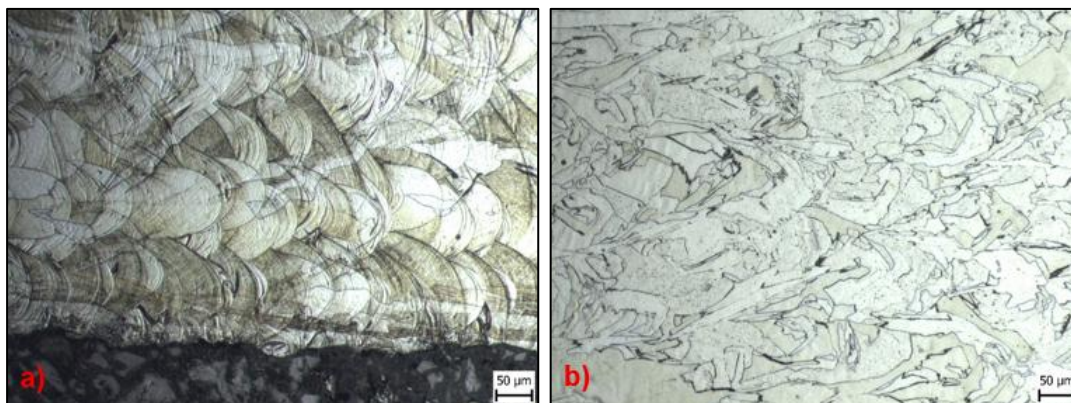


Figure 1 Microstructure of 3D printed AISI 316L in direction perpendicular to direction of application of individual layers, etched in V2, a) as-built, b) annealed

2.2 Mechanical properties

Flat tensile test specimens were used to evaluate changes in mechanical properties. The gauge length was 50 mm, width was 10 mm and thickness was 2 mm. The specimens were subjected to tensile loading using a 100kN testing machine until the fracture at a constant crosshead speed of 0.5 mm per minute, corresponding to a strain rate of 10^{-4} s^{-1} . Both hydrogen-free and hydrogen-charged specimens were tested in the as-built condition as well as after annealing.

To evaluate the susceptibility of additively manufactured AISI 316L steel to hydrogen embrittlement, the tensile specimens were electrolytically charged with hydrogen and subsequently subjected to slow strain rate tensile testing (SSRT) within three minutes after charging. Electrolytic hydrogen charging was performed in a 0.05 M sulfuric acid (H_2SO_4) solution prepared in 1 litre of distilled water with the addition of 1 g of KSCN. Thiocyanate-containing additives are commonly used as hydrogen recombination poisons to suppress the recombination of adsorbed atomic hydrogen into molecular hydrogen and to promote hydrogen absorption during electrochemical charging [9]. The specimen was connected as the cathode, while a platinum-coated tungsten mesh served as the anode. All specimens were charged for 8 hours at current densities of $1 \text{ mA}\cdot\text{cm}^{-2}$ and $5 \text{ mA}\cdot\text{cm}^{-2}$.

The susceptibility of the specimens to hydrogen embrittlement was evaluated using the hydrogen embrittlement index (HEI), calculated according to Equation (1).

$$HEI = \frac{A_0 - A_H}{A_0} \cdot 100 \% \quad (1)$$

where:

HEI – hydrogen embrittlement index (%)

A_0 - elongation of the uncharged sample (%)

A_H - elongation of the hydrogen-charged sample (%)

The results of the tensile tests are presented in **Table 2** and graphically shown in **Figure 2**. The effect of hydrogen slightly reduced the yield strength and slightly increased the tensile strength for all samples. However, the overall differences in strengths are negligible. Recrystallization annealing caused a reduction of the strength characteristics, specifically on average by 190 MPa for the yield strength and by 40 MPa for the tensile strength. The reduction in these values was caused by the transformation of the original non-equilibrium microstructure formed by melting pools and a cellular sub-structure into a homogeneous austenitic structure like conventionally produced 316L. During annealing, the melting pools dissolved, the

dislocation density decreased, residual stresses were relieved, and grains recrystallized, leading to a reduction in barriers to dislocation motion and thus to decreased mechanical strength and increased ductility.

Table 2 Mechanical properties of as built and annealed samples without hydrogen and after electrochemical charging

Sample	Re (MPa)	Rm (MPa)	A (%)	HEI (%)	HV1 (-)
as-built_without hydrogen	577	618	23.5	-	234 ± 4
as-built_1 mA·cm ⁻²	538	627	23.1	1.91	233 ± 6
as-built_5 mA·cm ⁻²	539	622	25.8	-9.79	237 ± 6
annealed_without hydrogen	368	576	30.1	-	196 ± 6
annealed_1 mA·cm ⁻²	360	578	32.3	-7.28	192 ± 6
annealed_5 mA·cm ⁻²	355	586	30.1	-0.03	196 ± 6

The Vickers hardness (HV1) was measured on the individual specimens under a load of 1 kg. The values presented in **Table 2** represent the average values from twenty measurements for each condition. The measurements were made on a DuraScan 70 G5 testing machine. As a result of recrystallization, the hardness values decreased for the same reasons as the strength properties. Hydrogen charging had no significant effect on the hardness of the material.

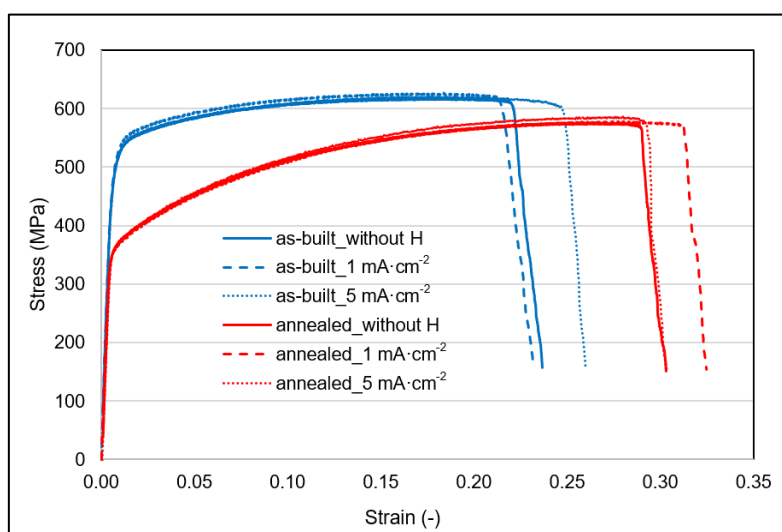


Figure 2 Stress–strain curves of additively manufactured 316L stainless steel in as-built and annealed conditions without hydrogen and after hydrogen charging at current densities of 1 and 5 mA·cm⁻².

A decrease in ductility values due to hydrogen exposure was expected. However, a reduction in ductility was observed only in the as-built condition after hydrogen charging at a current density of 1 mA·cm⁻². At the higher current density, the ductility increased approximately by 2.3 %. In the annealed state, a similar increase in ductility occurred at a lower current density, while at the higher current density the ductility remained nearly unchanged. Based on the ductility values, the hydrogen embrittlement index (HEI) was calculated, as shown in **Table 2**. The increased ductility values may be associated with the Hydrogen-Enhanced Localized Plasticity (HELP) mechanism. According to this theory, the presence of hydrogen enhances dislocation mobility and localizes deformation around crack tips, thereby enabling subcritical crack growth [2].

2.3 Fractographic analysis

Fractographic analysis was performed using a JEOL 6490LV scanning electron microscope in secondary electron (SE) mode. All specimens exhibited a predominantly transgranular ductile fracture characterized by dimple morphology (**Figure 3a**), with areas of brittle features with “fiber” morphology (**Figure 3b, c**).

In the as-built condition, crack initiation was associated with process-related defects such as partially melted powder particles and lack-of-fusion regions (Figure 3d), which could have acted as stress concentrators. The fracture surface also contained dimples and cavities.

Heat-treated specimens exhibited a higher fraction of quasi-cleavage fracture features compared to the as-built condition (**Figure 3c**). This behavior may be associated with microstructural imperfections persisting after heat treatment, as observed in **Figure 1b**. These heterogeneities can act as preferential sites for crack initiation and propagation, promoting localized deformation and the formation of flatter, faceted fracture regions.

Hydrogen-charged specimens had high fraction of quasi-cleavage fracture, especially near the surface, where flatter facets and locally brittle regions were present (**Figure 3b, c**). In subsurface regions, these brittle features were often combined with ductile fracture, indicating a mixed-mode fracture behavior. However, hydrogen did not significantly affect the overall fracture behavior.

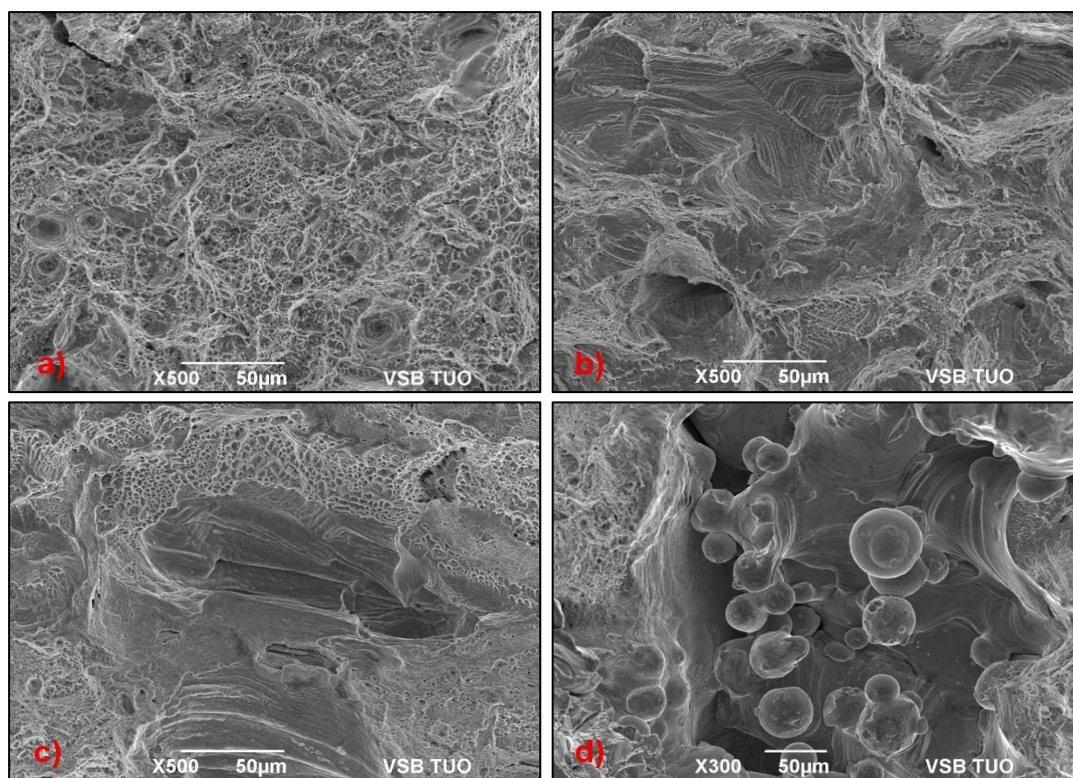


Figure 3 Details of fracture surfaces: a) heat treated without hydrogen, ductile fracture with dimples, b) as-built, hydrogen charged ($5 \text{ mA} \cdot \text{cm}^{-2}$), quasi-cleavage fracture, c) heat treated, hydrogen-charged ($1 \text{ mA} \cdot \text{cm}^{-2}$), quasi-cleavage fracture, d) as-built, hydrogen-charged ($1 \text{ mA} \cdot \text{cm}^{-2}$), subsurface unmelted powder particles

3. CONCLUSION

The aim of this work was to evaluate the effect of hydrogen embrittlement on additively manufactured AISI 316L steel produced by SLM technology in the as-built condition and after subsequent heat treatment. The

results indicate that the 3D-printed AISI 316L steel exhibits good resistance to hydrogen, even in the as-built condition. The results can be summarized in the following points:

- Heat treatment led to a decrease in hardness and strength due to microstructural homogenization, resulting in reduced dislocation density and the relief of residual stresses.
- No significant effect of hydrogen on the yield strength or ultimate tensile strength was observed in this study.
- Ductility was not significantly affected by hydrogen exposure. Further measurements will be necessary to achieve a better understanding of the observed ductility behaviour.
- Fractographic analysis indicated a transition from predominantly transgranular ductile fracture to locally mixed-mode fracture in hydrogen-charged specimens, with an increased occurrence of quasi-cleavage features near the surface.

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REFERENCES

- [1] SUN, B., ZHAO, H., DONG, X., TENG, C., ZHANG, A., KONG, S., ZHOU, J., ZHANG, X., TU, S. Current challenges in the utilization of hydrogen energy-a focused review on the issue of hydrogen-induced damage and embrittlement. *Advances in Applied Energy*. 2024, vol. 14, p. 100168. <https://doi.org/10.1016/j.adapen.2024.100168>.
- [2] CAVALIERE, Pasquale. *Hydrogen Embrittlement in Metals and Alloys*. Springer, 2025. ISBN 978-3-031-83680-0.
- [3] BHADESHIA, H. K. D. H. a R. W. K. HONEYCOMBE. *Steels: structure, properties, and design. 5th edition*. London: Butterworth-Heinemann, an imprint of Elsevier, 2024. ISBN 978-0-443-18491-8.
- [4] LIU, J., YANG, H., MENG, L., LIU, D., XU, T., XU, D., SHAO, X., SHAO, C., LI, S., ZHANG, P., ZHANG, Z. Significance of melt pool structure on the hydrogen embrittlement behavior of a selective laser-melted 316L austenitic stainless steel. *Materials*. 2023, vol. 16, p. 1741. <https://doi.org/10.3390/ma16041741>.
- [5] CLAEYS, L., DECONINCK, L., VERBEKEN, K., DEPOVER, T. Effect of additive manufacturing and subsequent heat and/or surface treatment on the hydrogen embrittlement sensitivity of 316L austenitic stainless steel. *International Journal of Hydrogen Energy*. 2023, vol. 48, no. 92, pp. 36142–36157. <https://doi.org/10.1016/j.ijhydene.2023.05.215>.
- [6] LIU, Q., Yan, Y., IQBAL, M.Z., TARIQ, M., BARNOUSH, A., AISSA, B., FARHAT, H. Enhanced hydrogen embrittlement resistance of directed energy deposition 316 L by post-manufacturing heat treatment. *NPJ Materials Degradation*. 2025, vol. 9. <https://doi.org/10.1038/s41529-025-00590-x>.
- [7] HLINKA, J., KRAUS, M., HAJNYS, J., PAGAC, M., PETRU, J., BRYTAN, Z., TANSKI, T. Complex corrosion properties of AISI 316L steel prepared by 3D printing technology for possible implant applications. *Materials*. 2020, vol. 13, p. 1527. <https://doi.org/10.3390/ma13071527>.
- [8] RENISHAW plc. *Data sheet: SS 316L-0407 powder for additive manufacturing*. [online]. 2017. [viewed: 2026-04-10]. Available from: <https://www.renishaw.com/cs/data-sheets-additive-manufacturing--42225?srsId=AfmBOorxlbKUOglPuU6a9k4QfzEIVYYAW0PQiapIDnQirjepyr2AaVb>.
- [9] KHALEGHIFAR, F., RAZEGHI, K., HEIDARZADEH, A., MOUSAVIAN, R.T. Effect of hydrogen on the tensile behavior of austenitic stainless steels 316L produced by laser-powder bed fusion. *Metals*. 2021, vol. 11, no. 4, p. 586. <https://doi.org/10.3390/met11040586>.