

Burst tests of orbital welded austenitic stainless steel (316L) tubes charged in pressurized hydrogen

Sam Shaanika

sam.shaanika@bam.de

BAM Federal Institute for Materials Research and Testing: Bundesanstalt für Materialforschung und -prüfung <https://orcid.org/0009-0007-4444-3128>

Thomas Boellinghaus

BAM Federal Institute for Materials Research and Testing: Bundesanstalt für Materialforschung und -prüfung

Oded Sobol

BAM Federal Institute for Materials Research and Testing: Bundesanstalt für Materialforschung und -prüfung

Thomas Alweendo

University of Namibia Faculty of Agriculture Engineering and Natural Resources

Oluwagbenga Johnson

University of Namibia Faculty of Agriculture Engineering and Natural Resources

Jan Schu

Orbital Welding Tools(OWT) GmbH

Timo Gugel

Orbital Welding Tools(OWT) GmbH

Research Article

Keywords: 316L, hydrogen assisted cracking, heat affected zone, burst pressure, orbital welding, heat input

Posted Date: June 1st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9692809/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Burst tests of orbital welded austenitic stainless steel (316L) tubes charged in pressurized hydrogen

Sam Shaanika^{a,b}, Thomas Böllinghaus^a, Oded Sobol^b, Thomas Alweendo^a, Oluwagbenga Johnson^a Jan Schu^c, Timo Gugel^c

Corresponding author: sshaanika@unam.na or sam.shaanika@bam.de

^a Faculty of Agriculture, Engineering and Science, University of Namibia (UNAM), Windhoek, Namibia

^b Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany

^c Orbital Welding Tools (OWT), Mülheim-Kärlich, Germany

Abstract

Orbital TIG welding is extensively used to weld tube to tube in many industries such as food, chemical oil and gas. Nowadays, applications in hydrogen transportation remains an interesting challenge due to the material susceptibility to hydrogen assisted cracking. Hydrogen can be introduced to the material during welding, fabrication or in-service as tube may be exposure to harsh environment that can be classified as internal or external hydrogen sources. In this study, a 316L (1.4404) cold drawn 1/2" (12.7 mm OD) and 3/8" (9.53 mm OD) tube with 0.5 mm wall thickness was investigated. Cold drawn tube sections were machined into hollow orbital welded specimen. Experimental assessment of burst testing of the welded specimens was performed and comparison of the high-pressure gaseous hydrogen autoclave precharged (1000 bar, 150 °C, 21 days) and non-precharged (controls). Precharged specimens showed modest increases in burst pressure ($\approx 2 - 8 \%$) relative to controls. Hydrogen degradation index was determined to quantify the susceptibility of material in the investigation conditions. Fractography revealed a ductile fracture morphology with coarser dimples, larger microvoids and secondary cracks present in the precharged specimens. Within the limits of the present replication, the data suggests that under the tested extreme charging condition 316L tubing retained burst capacity and did not exhibit classical hydrogen assisted cracking. The findings contribute to the understanding of compatibility of welded austenitic stainless steels for the green hydrogen applications.

Keywords: 316L, hydrogen assisted cracking, heat affected zone, burst pressure, orbital welding, heat input

1 Introduction

Green hydrogen infrastructure is expanding rapidly as nations pursue decarbonisation and energy storage goals, placing increasing demand on high-pressure components such as tubing, valves and dispensers used in refuelling stations and distribution manifolds. These components commonly operate at elevated pressures and temperatures; therefore their materials and joints must combine corrosion resistance, strength and robust fracture resistance in hydrogen environments to avoid catastrophic failure in service.

Austenitic stainless steels (ASS), commonly used in structural component including hydrogen electrolyzers, storage and transport systems which may operate under excessive and harsh conditions while exposed to hydrogen which may lead to hydrogen assisted cracking (HAC) or well-known hydrogen embrittlement (HE). Stainless steels, particularly 316L (1.4404) are use in the structural components used in several high and low temperature conditions such as small bores, fuel-cell vehicles, high pressure gas pipes, valves, fittings and springs typically in the hydrogen refueling settings. Components may require assembly which can be mechanical or weldment. Weldment when done properly offers competitive advantages over mechanical assembly as it provides a stronger, permanent and vibration or shock resistant joints, making it more cost and material effective and requires less maintenance compared to use of fasteners (mechanical assembly) as represented in Figure 1. Orbital tube welding is an effective joining strategy for gas handling and dispensing tubes. Orbital TIG welding of stainless steel is widely used in industries with welded tubes used to transport materials such as oil,

gas and other fluids. This tubing works under high-pressure, high temperature or otherwise harsh environment. Hydrogen economy and scaling up of hydrogen production material structural strength and integrity are of high concern to ensure the long-term safety and reliability. Consequently, the materials and welds in any metallic components need to be compatible for such applications, considering potentially damaging hydrogen-metal interactions. Specifically, hydrogen transport systems must be resistant to hydrogen degradation of the mechanical properties in terms of ductility, but sometimes also in strength, to avoid brittle, catastrophic cracking and fracture[1, 2].

The effects of gaseous hydrogen on austenitic stainless steels have been widely studied for many decades[3-9]. Hydrogen assisted fracture of welds has not been extensively characterized. In addition, different weld microstructures generally provide different hydrogen diffusion, absorption and trapping behaviours than the base materials. Thus, it generally needs to be ascertained that respective weld microstructures, especially those of the weld metal (WM) and heat affected zone (HAZ) will not become more sensitive compared to the base materials in pressurized hydrogen environments [10, 11]. Furthermore, welding is an assembling or repairing works is another challenging and interesting field worth of further investigations.

In this study, the aim is to evaluate tubing and welds that reflect the materials used in engineering industrial systems particularly for service with gaseous hydrogen. HAC fracture after burst testing was assessed. Burst pressure testing of the two tube geometries (1/2" (12.7 mm OD) and 3/8" (9.53 mm OD)) and wall thickness (0.5 mm) for the autoclave precharged and non-precharged specimens were compared to quantify the hydrogen susceptibility of the material. Hydrogen contents were measured by thermal desorption spectroscopy (TDS) and fracture surfaces were investigated in a scanning electron microscope (SEM).

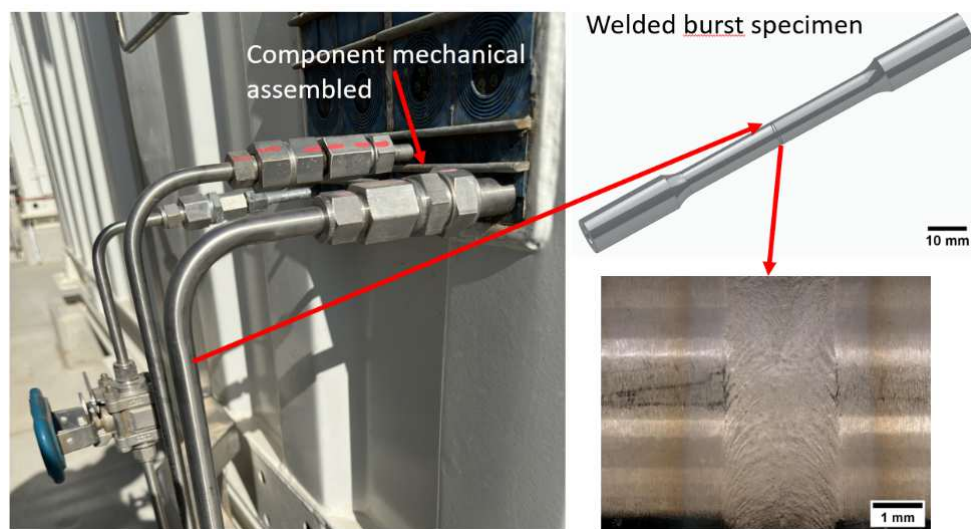


Figure 1. Tube component conversion to welded burst specimen design

2 Experimental

2.1 Materials

The material used in this study is grade 316L austenitic stainless steels, with chemical composition as shown in Table 1. Elemental analysis was determined by optical emission spectrometry (OES) using a SPECTROTEST (SPECTRO Analytical Instruments GmbH, Kleve, Germany) in the Fe-30-N mode. Measured composition are compared to data from the supplier certificate and standard nominal values.

Table 1. Chemical composition of the investigated materials measured using the OES and compared to the Nominal values according to DIN and ASME[12, 13](all values are in wt.%)

Material / composition element	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
1/2" (12.7 mm)	0.02	0.37	1.67	0.025	0.012	16.77	1.90	11.16	Bal.
3/8" (9.53 mm)	0.02	0.36	1.67	0.025	0.012	16.76	1.89	11.15	
Supplier	0.02	0.38	1.59	0.027	0.011	16.74	2.01	11.11	
Nominal	≤0.03	≤0.75	≤2.00	≤0.045	≤0.030	16.00 - 18.00	2.00- 3.00	10.00- 14.00	

In Table 2, the mechanical properties, which include measurement of tensile strength, yield strength elongation and hardness as obtained from the supplier certificates of the investigated materials are listed. It can be noted that 3/8" pipe exhibits a higher strength at a lower ductility than the 1/2" pipe. These properties offers a comprehensive base and understanding of the material's behaviour when subjected to various loads and stress conditions.

Table 2. Mechanical properties of the 316L as per certificate provided by the supplier

316L (1.4404)	Yield Strength 0.2% MPa	Tensile Strength MPa	Elongation %	Hardness HRC
Nominal values	518 -758	724-965	min. 20	max. 30
1/2" (12.7 mm)	674	744	32.5	27
3/8" (9.53 mm)	751	803	20.4	26

2.2 Specimen Preparation

The seamless cold drawn tube components were converted into a weld burst test specimen of the two geometries as per design shown in Figure 2. The inner surface finishes and conditions of the specimen was kept in the same state as for the tubing real industrial operational case. The weld specimens were cleaned and taken for autoclave precharging in high-pressure gaseous hydrogen at 1000 bar, 150 °C, for 21 days, and are designated as Welded-P. In accordance with DIN EN ISO 3690[14], after gaseous hydrogen precharging, the specimens were stored in the liquid nitrogen (-196°C) for hydrogen preservation for the duration not longer than three weeks before SSRT test or hydrogen content measurement. To establish the material hydrogen uptake, small coupon of tubes with length of 20 mm were cut and taken hydrogen measurement for the precharged and none-precharged in both CD and HT state. Coupons or SSRT specimen after taken out of the high-pressure autoclave charging in less than 120 s exposure time were stored in the liquid nitrogen cylinder as per the practice to prevent hydrogen egress. Before SSRT testing or hydrogen content measurement, the specimens were defrosted and cleaned in ethanol (Ultrasonic bathed) for 120 s and subsequently blown with gaseous nitrogen for drying and further residues removal for about 60 s.

For the hydrogen content measurement, the coupons are weighed and the mass transferred for further measurement utilising the carrier gas hot extraction (CGHE) technique with a Galileo G8 (Bruker corporation, Billerica, USA). The CGHE coupled with mass spectrometer (MS) ESD 1000 from InProcess Instruments. The coupon (sample) is heated inside the glass tube using an infrared radiation-emitting furnace, labelled -IR07 of the G8 system. By thermally activating from ambient temperature to

800°C, the diffusible hydrogen content present in coupon and employing a carrier gas stream of nitrogen (N₂), the hydrogen is transported to the MS detection chamber, measured and recorded accordingly.

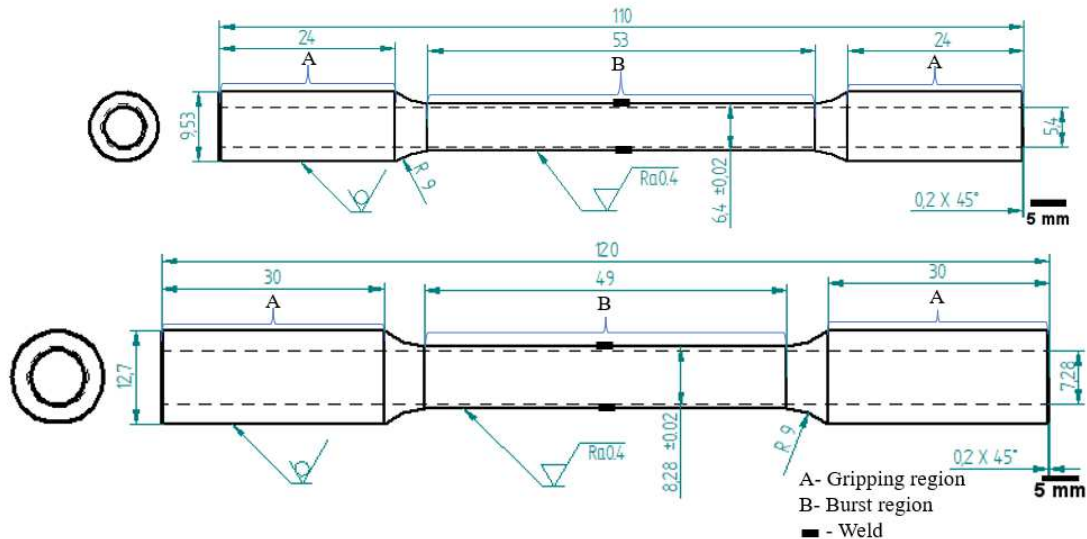


Figure 2. Geometry and Dimensions of the welded burst test specimens (all dimensions in mm)

2.3 Orbital welding

The specimen preparation for the weld specimen from the original machined cold drawn specimen has involved the following steps in the sequence: cut, squared to remove all the burrs, surface fit and weldment as illustrate in Figure 3. The type of welding head equipment is closed arc welding (CHW 38) and welding sources all supplied by Orbital Welding Tools (OWT) GmbH, (Mülheim-Kärlich, Germany). The automated Gas Tungsten Arc Welding (GTAW) machine was used produce butt weld without filler material. The machine offers high -quality, precise orbital tube welds with low spatter and great weld pool management. The welding was done in auto mode and takes a total welding time of 87 s. The automation ensures welding consistency, repeatability with minimal human error, therefore making the Orbital welding the best technology for tube welding or large-scale production.

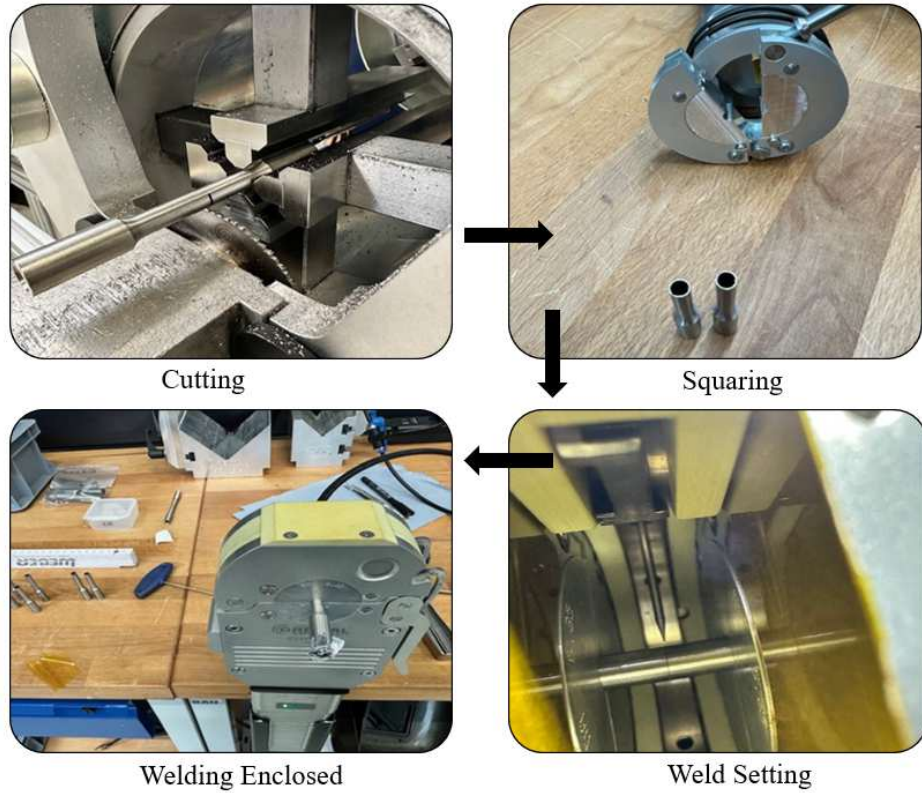


Figure 3. Orbital welding processes followed to prepare burst weld specimen (not to scale)

$$HI = \frac{\eta \times U \times I}{V_s} \quad (1)$$

Where HI represent heat input (J/mm), η is the weld thermal efficiency constant, which is typically 0.6 for the GTAW (TIG) welding method, U is the arc voltage (V), I is the current (A) and finally V_s is the travel speed (mm/s) as shown in Table 3. besides, other welding parameters are fixed such as welding speed 2 mm/s, electrode diameter 1.6 mm, electrode spacing 1.2 mm and finally shielding gas Argon (5.0) with a flow rate 2.5 l/min.

Table 3. experimental parameters and calculated HI values

No	Angle (°)	I (A)	U (V)	HI(J/mm)
1	0-90	37.25	8.0	89.40
2	90-180	34.35	7.9	81.41
3	180-270	33.9	7.6	77.29
4	270-365	31.95	7.6	72.85

Heat input plays a critical role in forming welding joints during the welding process. Therefore, suitable heat input parameters provide the weld complete penetration. If the HI is too high, it will cause the weld to overheat, burn and poor quality. If the HI is too low, the base metal will not be melted sufficiently, leading to poor penetration depth of the weld joints. Singh et al [15], Baskoro et al [16] and many others have to optimize the HI parameters to improve the orbital welding quality specifically in the 316L.

2.4 Microstructure

The microstructures of the specimen were observed after cutting, moulding, grinding, polishing and etching. The specimens were inspected metallographically using the Beraha II (BII) colour etchant and were investigated in the longitudinal section (LS) and cross-sectional (CS) orientation of the tube. The

BII etchant consists of 48 g of ammonium difluoride, 800 ml of distilled water, and 400 ml of concentrated hydrochloric acid. Therefore, a 100 ml of stock solution for BII etchant and 1 g of potassium bisulphite was used for a duration between 5 to 20 seconds. The austenite grains vary in colour after etching with BII, depending on the grain orientation, segregation, etching time and solution concentration.

Welding causes the formation of three separate metal zone with different microstructures, and unique properties: The heat affected zone (HAZ), the weld metal (WM) and the unaffected base metal (BM) as illustrated in Figure 4 and Figure 5 presenting the two size tube specimens cut in the longitudinal orientation. The HAZ is further divided into four sub-zones which are the coarse grain (CGHAZ), fine grain (FGHAZ), Intercritical (ICHAZ) and subcritical (SCHAZ) as presented in Figure 6. The HAZ does not melt however undergoes a high temperature cycle that may change its mechanical properties such as toughness, ductility and hardness. This change might improve or worsen the welded joints performance based on the material, welding condition and operational environment. Generally, 316L base metal is austenitic, during welding it solidifies as delta (δ) ferrite and then transforms back to austenite leaving some residual ferrite in the weld metal. The amount of ferrite expected for the welds on various product form and chemical compositions of the stainless steels is critical as may affect degradation resistance. In addition, proper inert gas purging is necessary to prevent the formation of heat tint during welding. The amount of heat tint (color) produced during welding is proportional to the amount of oxygen and or moisture in the purge gas and has a direct on the degradation resistance of the weldment.

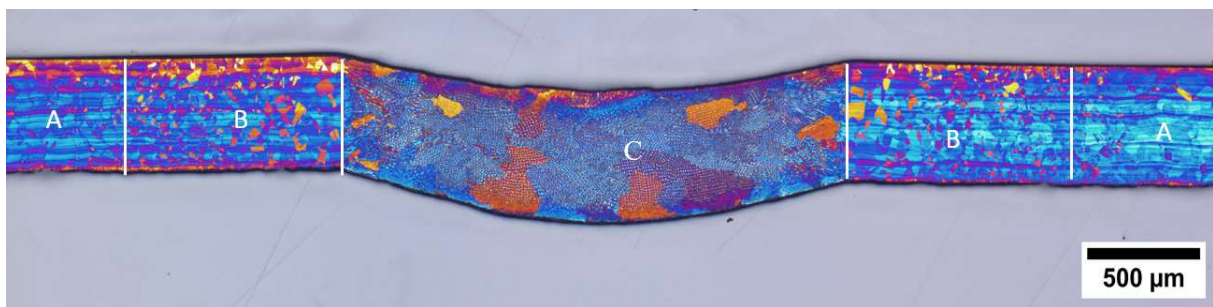


Figure 4. Microstructure of the 316L etched in BII for the 1/2" (12.7 mm) specimen in the Longitudinal section (a) Fine grain HAZ, (b) Coarse grain HAZ and (c) WM

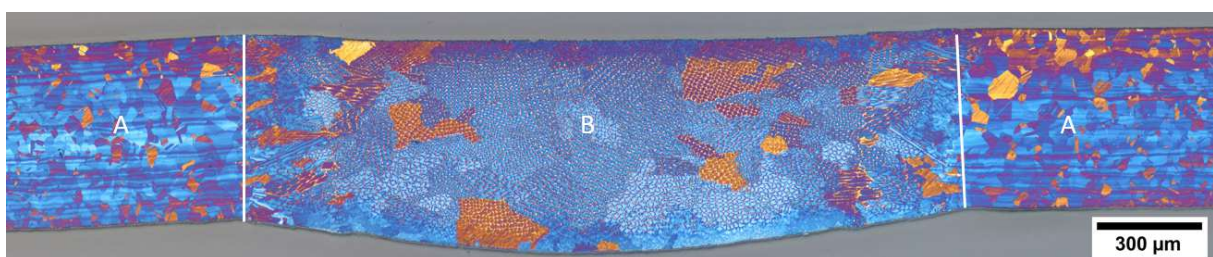


Figure 5. Microstructure of the 316L etched in BII for the 3/8" (9.53 mm) specimen in the longitudinal section (a) HAZ and (b) WM

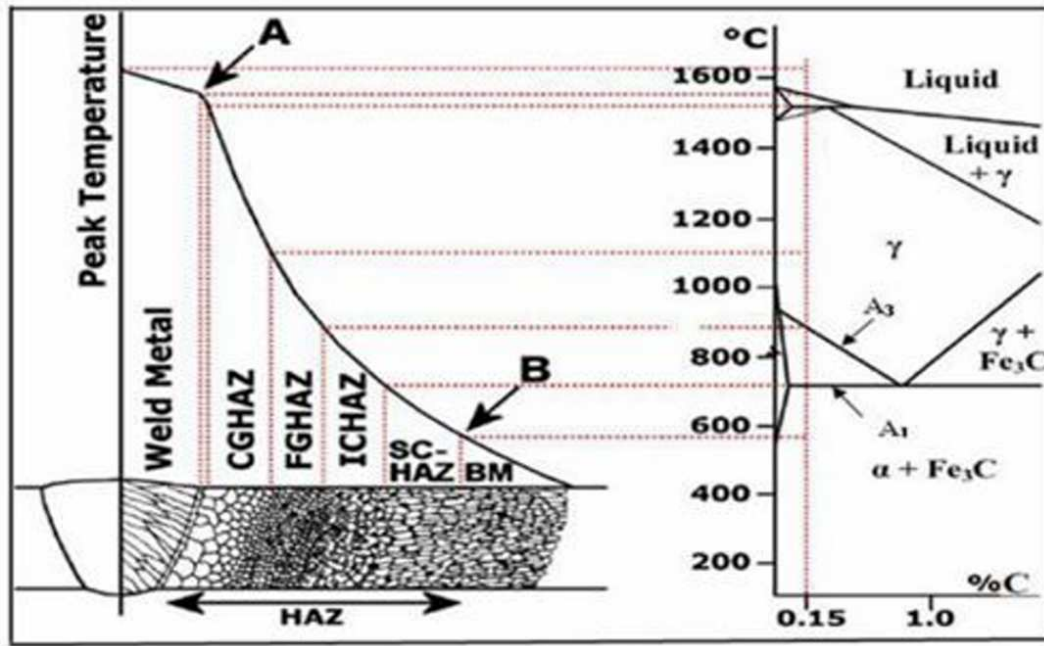


Figure 6. Heat affected zone schematic between A-B[17].

Table 4 presents the grain size measurement of the investigated tubes in weld state and in the longitudinal orientations. It is worth noting that different welding zones have indeed different grain sizes as well as different hardness. The WM has a lower hardness compared to the HAZ. It is also evident that large the grain size the lower hardness. Similar, in reverse, the smaller the grain sizes the higher the hardness values.

Table 4. Grain size measurement of the two tubes in longitudinal sections (LS) orientation.

Materials	Grain size (μm)	Area (μm^2)	Hardness (HV)
316L (1.4404)	ASTM Norm		
W 1/2" (12.7 mm) LS-WM	6.83 ± 0.12	1306.8 ± 89.71	145.88 ± 3.72
W 1/2" (12.7 mm) LS HAZ	9 ± 0.28	284.85 ± 85.63	230.86 ± 30.32
W 3/8" (9.53 mm) LS-WM	7.87 ± 0.06	637.67 ± 22.55	151.5 ± 6.99
W 3/8" (9.53 mm) LS-HAZ	9.1 ± 0.57	277.3 ± 105.92	228 ± 30.03

2.5 Burst Test

Hydrostatic burst tests were performed as per the schematic illustration and setup shown in Figure 7, using a Dustec Hochdrucktechnik machine with maximum allowable testing pressure of 2500 bar. Test replication was limited to (burst tests: $n=3$ for non-precharged and $n=2$ for precharged) conditions were conducted for both tube sizes. All burst tests were conducted at ambient temperature and pressure rate of 50 bar per minute until fracture. Before testing, specimens stored in liquid nitrogen were placed in ethanol for cleaning and warmed in the ambient environment to room temperature. Specimens were continuously fluid pressurized until fracture while monitor and record pressure, time, volume etc are recorded.

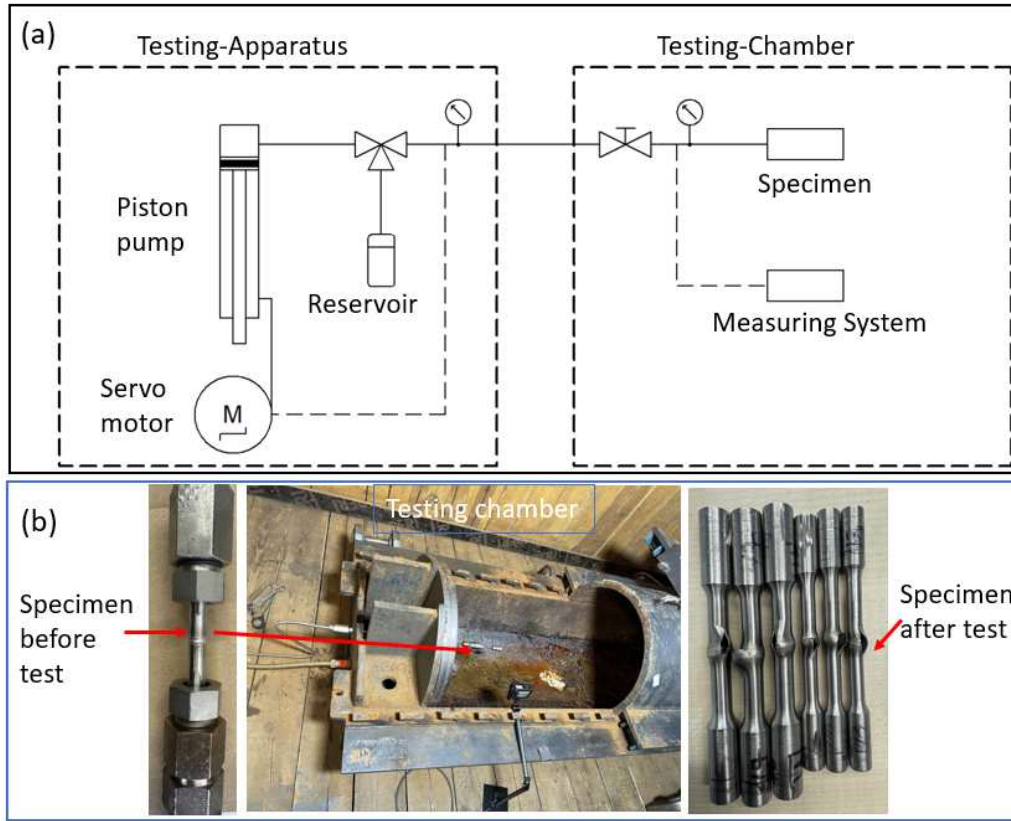


Figure 7. Burst testing layout (a) and set up (b)

Pressure expressed by the tubes, pipeline or round vessels in operations undergoes two types of stress, transverse and longitudinal. The transverse (circumferential or tangential) also known as hoop stress acts along the circumference of the tube caused by internal fluid pressure, meanwhile longitudinal stress acts perpendicular to the tube's axis. According to ASME B31.3, outlined various calculate the critical stresses and burst pressure common formula are derived from Barlow Equation. this study, the predicted burst pressure according to ASME [18], namely by the Barlow's equation [19], was used:

$$\sigma_T = \frac{PD}{2t} \quad (2)$$

Where σ_T is the transverse stress, P is the internal pressure, and t is wall thickness

$$\sigma_L = \frac{PD}{4t} \quad (3)$$

Where σ_L is the longitudinal stress, P is the internal pressure and t is wall thickness

To determine the burst pressure representing a critical factor in assessing the structural integrity of a tubing, it can be estimated using the Equation (4).

$$BP = \frac{2 \cdot S \cdot t}{D_o} \quad (4)$$

with BP: Burst pressure, S: Ultimate tensile strength, t: Wall thickness and D_o : Tube outer diameter of the tube within the burst region.

To quantify the effects of hydrogen on the mechanical properties an embrittlement index is introduced here, according to Equation (5).

$$HDI = \frac{BP_{NP} - BP_P}{BP_{NP}} \cdot 100 \quad (5)$$

with HDI (%): Hydrogen degradation index, BP_{NP} : Burst pressure in the non-precharged state and BP_P : Burst pressure in the hydrogen precharged state.

The degradation index can generally be used to quantify the sensitivity of the material against hydrogen absorption and respective property degradation in the burst tests.

3 Results and Discussion

3.1 Mechanical Testing

Hydrogen measurement of the cold drawn precharged and non-precharged were recorded as means of 5.5 ± 0.14 and 82 ± 10.77 ppm, respectively. Comparing all experimentally determined burst pressure data, it becomes obvious that for all precharged conditions an increase in burst pressure can be observed as compared to the non-precharged specimens. Comparing the geometry influence, the 3/8" (9.53 mm OD) has a higher pressure to the 1/2" (12.7 mm OD) specimen regardless of whether precharged or non-precharged. The precharged specimen shows an increase in burst pressure compared to non-precharged in both test tube size as shown in Figure 7 and Figure 8, tentatively. The calculate degradation index according to equation (5), present the index values of -1.87 % and -3.31% for the 1/2" (12.7 mm OD) and 3/8" (9.53 mm OD), respectively. Figures 8 (a) and (b), presents the burst pressure vs time graphs presenting the results of the tested 1/2" (12.7 mm) and 3/8" (9.53 mm) in the precharged (red line) and non-precharged (black line). Comparison of all figures underpin the above-mentioned increase of burst pressure for all precharged specimens, regardless of the geometry although more pronounced in the 3/8" tube.

The increase in burst pressure after precharging reveals the possibility of increase in strength of material. Moreover, similar observation is made in the burst test of precharged specimens in the cold drawn and heat-treated (joule heated) states[20] . Meanwhile the negative index values ascribe to the increase other than decrease of the mechanical properties. These provide an assumption of HAC strengthening mechanism. Strengthening mechanisms have reported by Robertson et al [21] [22], Sofronis et al [23] and many other researchers. It is assumed that strengthening is attributed to an enhanced dislocation movement, increased twinning and other effects caused by hydrogen in fcc microstructures. It can tentatively be anticipated here that hydrogen entering the fcc material in high concentrations pile up at grain boundaries for instance during straining the material during pressurizing and then finally results in a higher burst pressure, indicating some strengthening.

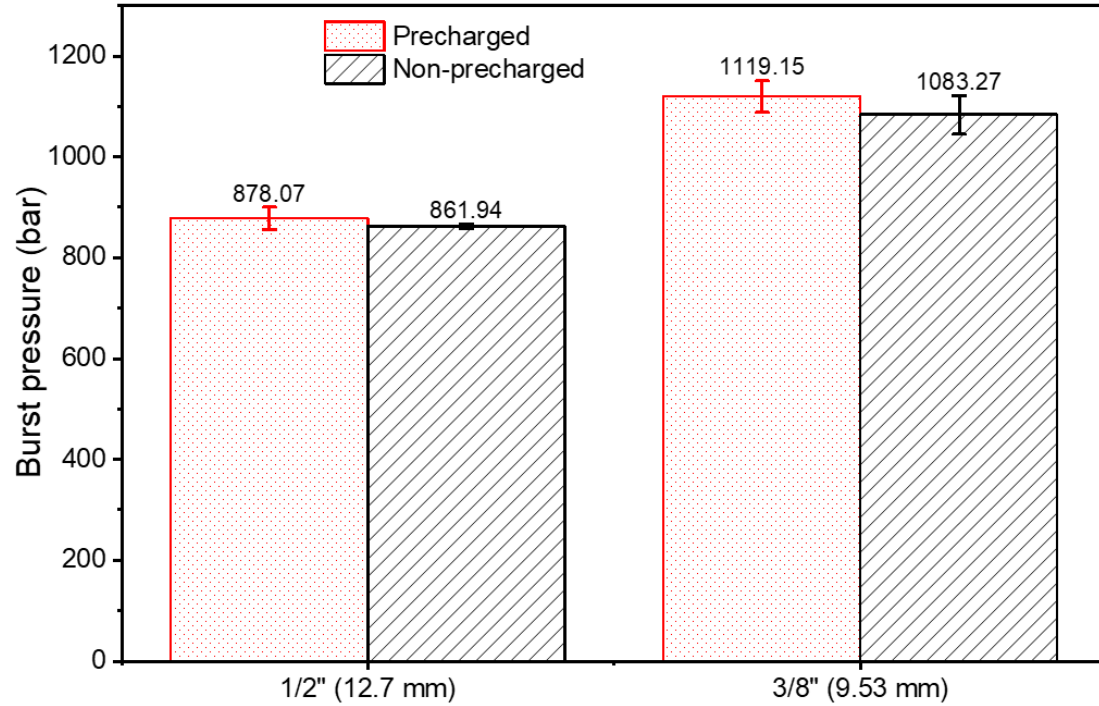


Figure 8. Experimental average burst pressure for the different welded tube size

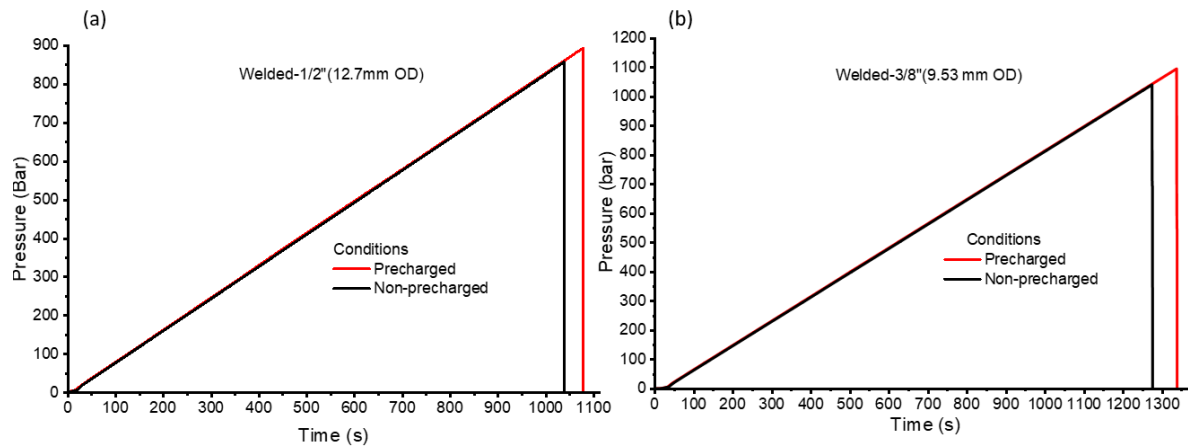


Figure 9. Pressure-time graphs for the burst test of 1/2" (12.7 mm) and 3/8" (9.53 mm) specimens.

3.2 Fractographic analysis

The fracture morphology of all specimens was examined utilizing a Keyence Optic VHX-5000 digital microscope and a table-top SEM to characterise the macroscopic and microscopic features of the fracture surfaces. The fracture surface all cracks path along the longitudinal orientation adhering to the theoretical equation (2) and (3).

Generally, the fracture surfaces of the tested specimens exhibit typical ductile characteristics with some pronounced different dimple, voids, cleavage facet and secondary cracks of varying sizes or different pattern between the precharged and non-precharged specimens. Figure 10 (a) - (c) represent the non-precharged, meanwhile Figure 10 (d) - (f) represent the precharged specimen, respectively. The non-precharged is characterized with honeycomb features, shallower, small dimples and voids. whereas the precharged specimens are characterized by somewhat deeper and elongated dimples, wider voids and

more secondary cracks. In addition, some features at least tentatively indicating a tendency to cleavage facet can be observed for the precharged specimens.

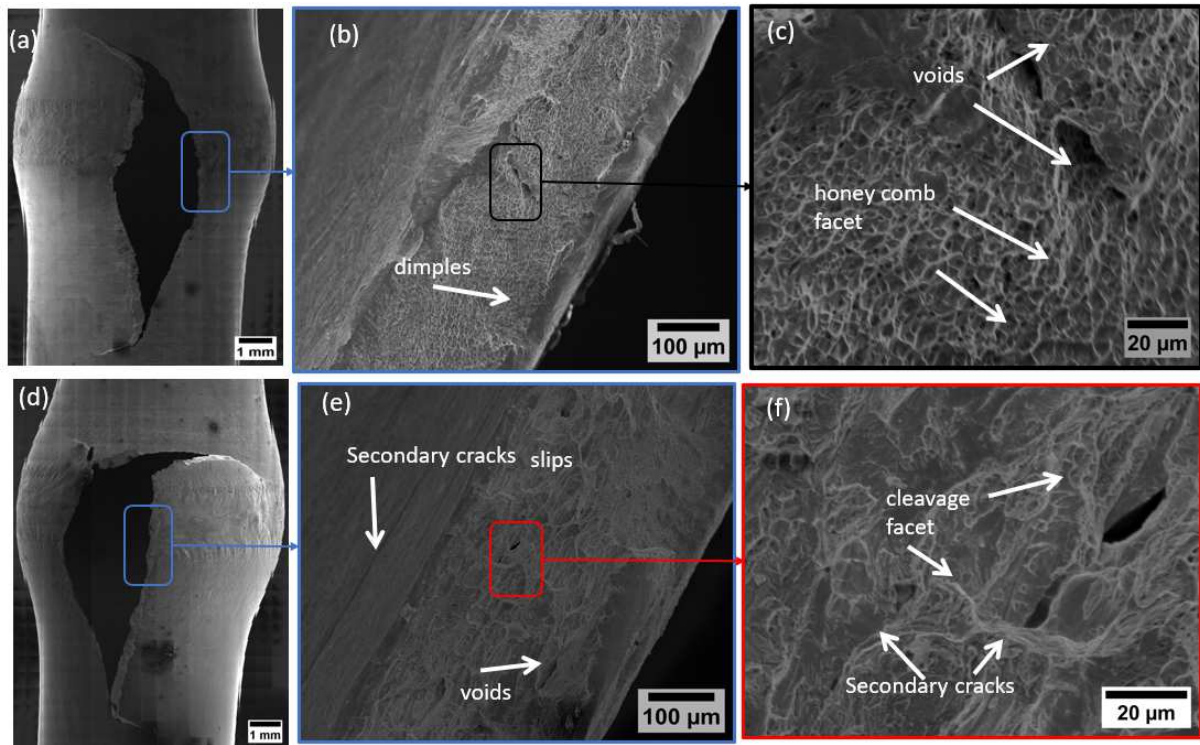


Figure 10. SEM Fracture surfaces for the welded 3/8 specimens (a) – (c) Non-precharged and (c) – (f) Precharged

It is noteworthy to observed that the fracture deforms with the knuckle-bone feature like which is formed around the weld material and HAZ regions. This feature can easily be observed due the excessive expansion of the tube geometry beyond the original tube size.

4 Conclusions

For the present study, Orbital TIG welded tubes of 1/2" (12.7 mm OD) and 3/8" (9.53 mm OD) tube with thickness 0.5 mm were subjected hydrostatic burst pressure tests to evaluate how hydrogen absorbed from pressurized gaseous environments might affect the fracture behaviour. The results lead to the following conclusions:

1. Orbital welding technology is well suited for the tube welding owing to its accuracy, reliable, efficient and high-quality welds which is critical for large scale industrial applications which include green hydrogen, oil and gas etc.
2. All tested specimens have shown a higher burst pressure for the hydrogen precharged condition, as compared to the non-precharged specimens. Such increase in burst pressure is consistent with precharged and indicate strengthening effects, with the negligible hydrogen degradation index.
3. The fractures surfaces observed are characterized as ductile fracture mode with morphology features of shallow to deep dimples to a transition of cleavage fractures distinguishing between precharged and non-precharged.
4. The burst pressure data revealed in this study show that hydrogen absorption in the investigated Orbital welded 316L entails some increase in burst strength which is relevant for the safe usage of this material for the design of high hydrogen pressurized tube sections.

References

- [1] J. Hoschke *et al.*, "The Influence of Subcritical Annealing and Cold Working on the Hydrogen Embrittlement Susceptibility of X65 D Pipeline Steel," *Materials and Corrosion*, vol. n/a, no. n/a, 2025, doi: <https://doi.org/10.1002/maco.202514934>.
- [2] M. A. Tunes *et al.*, "Limitations of Hydrogen Detection After 150 Years of Research on Hydrogen Embrittlement," *Adv Eng Mater*, vol. 26, no. 19, p. 2400776, 2024, doi: <https://doi.org/10.1002/adem.202400776>.
- [3] G. R. Caskey JR., *Hydrogen Compatibility Handbook for Stainless Steels*. USA: Du Pont de Nemours (E.I.) and Co., Aiken, SC (USA). Savannah River Lab., 1983.
- [4] K. Matsumoto, M. Hatano, S. Ohmiya, and H. Fujii, "Influence of Internal Hydrogen on Mechanical Properties of Nitrogen-added Austenitic Stainless Steel with Reduced Amount of Nickel and Molybdenum," *Tetsu-to-Hagane*, vol. 103, no. 1, pp. 54–63, 2017, doi: 10.2355/tetsutohagane.TETSU-2016-045.
- [5] B. P. Somerday, P. Sofronis, K. A. Nibur, C. San Marchi, and R. Kirchheim, "Elucidating the variables affecting accelerated fatigue crack growth of steels in hydrogen gas with low oxygen concentrations," *Acta Materialia*, vol. 61, no. 16, pp. 6153–6170, 2013, doi: <https://doi.org/10.1016/j.actamat.2013.07.001>.
- [6] L. A. Hughes, B. P. Somerday, D. K. Balch, and C. S. Marchi, "Hydrogen compatibility of austenitic stainless steel tubing and orbital tube welds," (in English), *International Journal of Hydrogen Energy*, vol. 39, no. 35, pp. 20585–20590, Dec 3 2014, doi: 10.1016/j.ijhydene.2014.03.229.
- [7] T. Freitas *et al.*, "Tensile testing in high-pressure gaseous hydrogen using the hollow specimen method," *MRS Bulletin*, vol. 49, no. 11, pp. 1112–1120, 2024/11/01 2024, doi: <https://doi.org/10.1557/s43577-024-00776-9>.
- [8] T. Michler, "Toughness and hydrogen compatibility of austenitic stainless steel welds at cryogenic temperatures," (in English), *International Journal of Hydrogen Energy*, vol. 32, no. 16, pp. 4081–4088, Nov 2007, doi: 10.1016/j.ijhydene.2007.03.009.
- [9] S. Fukuyama, M. Imade, T. Iijima, and K. Yokogawa, "Development of New Material Testing Apparatus in 230 MPa Hydrogen and Evaluation of Hydrogen Gas Embrittlement of Metals," in *ASME 2008 Pressure Vessels and Piping Conference*, 2008, vol. Volume 6: Materials and Fabrication, Parts A and B, pp. 235–240, doi: 10.1115/pvp2008-61849. [Online]. Available: <https://doi.org/10.1115/PVP2008-61849>
- [10] G. Sasikala, S. L. Mannan, M. D. Mathew, and K. B. Rao, "Creep deformation and fracture behavior of types 316 and 316L(N) stainless steels and their weld metals," *Metallurgical and Materials Transactions A*, vol. 31, no. 4, pp. 1175–1185, 2000/04/01 2000, doi: <https://doi.org/10.1007/s11661-000-0113-3>.
- [11] M. Rhode, "Hydrogen diffusion and effect on degradation in welded microstructures of creep-resistant low-alloyed steels," Band 148 Dissertation, Fakultät für Maschinenbau, Otto-von-Guericke Universität Magdeburg, Berlin, 2016. [Online]. Available: <https://www.tib.eu/de/suchen/id/TIBKAT%3A866572376>
- [12] ASTM A276, *Standard Specification for Stainless Steel Bars and Shapes*, A. International, West Conshohocken, PA, 2024 2024. [Online]. Available: https://www.astm.org/a0276_a0276m-24a.html
- [13] *Stainless Steels—Part 1: List of Stainless Steels, Appendix, E*, Deutsches Institut für Normung e.V., 2014.
- [14] *DIN EN ISO 3690:2018: Schweißen und verwandte Prozesse - Bestimmung des Wasserstoffgehaltes im Lichtbogenschweißgut*, DIN, 2018.
- [15] N. K. a. P. Singh, S.K, "Experimental and numerical investigations of pipe orbital welding process," *Materials Today*, vol. Proceedings, no. 27, pp. 2964–2969, 2020.
- [16] A. S. W. Baskoro, A; Prasetyo, E and Kiswanto, G, "The Taguchi and Response Surface Method for Optimizing Orbital Pipe Welding Parameters in Pulsed Current Gas Tungsten Arc Welding

(PC-GTAW) for SS316L," *Transactions of the Indian Institute of Metals*, no. 77(6):1607-1620, pp. 1–14, 2024, doi:

<https://doi.org/10.1007/s12666-023-03254-z>.

- [17] E. B. Prasetyo, A.S;Widyianto, A, "Effect of weaving speed on mechanical properties of stainless steel 316L Pipe in orbital gas tungsten arc welding," *Journal of Physics*, vol. 2972, Conference Series, 2025.
- [18] - *The American Society of Mechanical Engineers,B31.12 - Hydrogen Piping and Pipelines*, ASME, 2019.
- [19] M. R. Forouzan, S. M. Mirfalah Nasiri, A. Mokhtari, A. Heidari, and S. J. Golestaneh, "Residual stress prediction in submerged arc welded spiral pipes," *Mater Design*, vol. 33, pp. 384–394, 2012/01/01/ 2012, doi: <https://doi.org/10.1016/j.matdes.2011.04.016>.
- [20] S. Shaanika, T. Böllinghaus, O. Sobol, T. Alweendo, E. Krafft, and S. Ravi, "Burst tests of cold drawn and heat treated austenitic stainless steel (316L) tubes charged in pressurized hydrogen," *Welding in the world*, 2026, doi: <https://doi.org/10.1007/s40194-026-02448-5>.
- [21] I. M. Robertson and H. K. Birnbaum, "DISLOCATION MOBILITY AND HYDROGEN – A BRIEF REVIEW," presented at the 11th International conference on Fracture, Turin, Italy, 2005, 5759. [Online]. Available: <https://www.gruppofrattura.it/ocs/index.php/ICF/ICF11/paper/view/10864/10193>.
- [22] I. M. Robertson *et al.*, "Hydrogen embrittlement understood," *Metallurgical and materials transactions A*, vol. 46, pp. 2323–2341, 2015, doi: <https://doi.org/10.1007/s11661-015-2836-1>.
- [23] P. Sofronis and I. M. and Robertson, "Transmission electron microscopy observations and micromechanical/continuum models for the effect of hydrogen on the mechanical behaviour of metals," *Philosophical Magazine A*, vol. 82, no. 17-18, pp. 3405–3413, 2002/11/01 2002, doi: 10.1080/01418610208240451.

Acknowledgements

The authors would like to thank Cleanergy Solutions Namibia for the interest and the technical support in this study. Parts of the study have been conducted under the German-Namibian Joint Call of Intent funded by BMFTR. In this connection the continuous interest and engagement of PTJ, Mrs. Kerstin Annassi, is gratefully acknowledged. Major thanks of the authors also go to Zephanja Krzysch, Jonathan Nietzke, Maier Frederek, Enis, David Pöhlige, Andreas Kriegsmann, Swen Scheider, Enis Askar, Sebastian Simon, Christoph Opitz, Tobias Mente and Marina Marten for their discussions and untired support during measurements, metallography, test set-up and discussions of the manuscript. Further appreciation go to OWT GmbH and more specifically to Timo Gugel for assisting with the orbital welding of the specimens.

Author contribution

Conceptualisation: Sam Shaanika. Methodology: Sam Shaanika, Thomas Böllinghaus. Formal analysis and investigation: Sam Shaanika. Results and Discussion: Sam Shaanika, Thomas Böllinghaus, Writing: Sam Shaanika, Thomas Böllinghaus, Oluwagbenga Johnson; orbital weldment: Jan Schu and Timo Gugel. Supervision: Thomas Böllinghaus, Oded Sobol, Thomas Alweendo and Oluwagbenga Johnson.

Funding: This study was partly funded within the BMBF Project MaCoSa as a part of the German-Namibian Joint Communiqué of Interest.

Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest: The authors declare no competing interests.