

Article

LPBF Fabrication of 17-4 PH Stainless Steel TPMS Structures and Wettability of Surface-Treated Flat Plates

Fatema Tuz Zohra *, Hribhu Chowdhury  and Bahram Asiabanpour 

Ingram School of Engineering, Texas State University, San Marcos, TX 78666, USA; nsj27@txstate.edu (H.C.); ba13@txstate.edu (B.A.)

* Correspondence: fatema_zohra@txstate.edu

Abstract

This study investigates the laser powder bed fusion (LPBF) fabrication of 17-4 PH stainless steel triply periodic minimal surface (TPMS) structures and the wettability response of corresponding flat plates subjected to selected post-processing treatments. Five TPMS geometries were fabricated and visually examined to document their overall condition and manufacturing irregularities. Thermal aging, steel shot blasting, commercial hydrophobic coating, and selected treatment combinations were evaluated on flat plates manufactured using the same material and LPBF process. Wettability was assessed using time-dependent static contact angle (CA) measurements and a preliminary comparison of three steel shot grades. The fabricated TPMS structures retained their overall geometries but exhibited localized burnt edges, distortion of thin boundary features, and differences in surface appearance. The untreated LPBF-fabricated surface was hydrophilic and exhibited time-dependent wetting, with the CA decreasing from approximately 81° to as low as 48° within 4 min and complete wetting occurring within approximately 8–10 min. Among the evaluated blasting media, S-330 produced the highest CA values; however, blasted surfaces remained hydrophilic, and the response depended on whether the plate was untreated or aged. The coating produced CA of approximately 153–170° across all coated regions, both with and without prior blasting. These findings identify manufacturing considerations for LPBF-fabricated TPMS structures and demonstrate the effects of the investigated treatments on the wettability of corresponding flat surfaces, thereby providing insights for future studies of TPMS-based condensation surfaces in atmospheric water generation applications.

Keywords: triply periodic minimal surface (TPMS); 17-4 PH stainless steel; laser powder bed fusion (LPBF); surface engineering; contact angle (CA); wettability



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1. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, has emerged as a transformative technology for fabricating complex geometries that are difficult to produce using conventional manufacturing techniques [1,2]. Among these, triply periodic minimal surface (TPMS) structures have gained significant attention due to their geometric characteristics, including continuous curvature and high surface-area-to-volume ratios, which make them attractive candidates for applications involving heat and mass transfer, lightweight structures, and fluid transport [3–5]. Compared with traditional subtractive manufacturing, which removes material through machining processes and generates sig-

nificant waste, AM builds components layer by layer from feedstock material, enabling near-net-shape fabrication and improved material efficiency [6,7].

Laser powder bed fusion (LPBF), also known as selective laser melting (SLM), is widely used to manufacture geometrically complex metal components [8–10]. In LPBF, a digital model is sliced into successive layers, and the corresponding regions of a metal powder bed are selectively melted using a laser to form the intended geometry [11,12]. Despite its advantages, LPBF-produced components can exhibit defects or irregularities such as porosity, balling, cracking, and surface roughness because of the melting and rapid-solidification conditions associated with the process [13]. These process-induced features can affect component quality and surface characteristics, making process control and post-processing important considerations. While AM enables substantial design flexibility and supports applications across the aerospace, biomedical, and energy sectors, challenges remain in terms of process repeatability, surface finish, material qualification, and secondary post-processing requirements [14,15]. These considerations are particularly relevant to TPMS structures because their curved surfaces, thin features, and unsupported regions can present fabrication challenges, while their nonplanar geometries complicate direct surface evaluation.

Surface characteristics play a critical role in determining the functional behavior of AM-fabricated components, particularly in applications involving liquid-surface interactions. Wettability, typically quantified by contact angle (CA), is a key parameter used to characterize such interactions. Previous studies have demonstrated time-dependent wettability transitions on stainless-steel (SS) surfaces, where initially hydrophilic surfaces can evolve toward hydrophobic states because of changes in surface chemistry and environmental exposure [16,17]. Transitions from partial to complete wetting have also been reported under other surface and measurement conditions. Additionally, wetting transitions such as the Cassie-to-Wenzel transition illustrate how surface features and external forces can alter droplet behavior [18]. Collectively, these studies indicate that surface chemistry and surface structure can both influence wetting behavior.

Surface engineering at the micro- and nanoscale is therefore used to tailor wettability and modify liquid-surface interactions on SS surfaces [19]. Although SS is widely used due to its corrosion resistance, durability, electrical conductivity, and mechanical strength [20–24], it remains susceptible to degradation in specific industrial environments. This can lead to performance losses and necessitate surface modification to support long-term reliability [25]. For applications involving liquid-surface interactions, the inherent wettability of an SS surface may differ from the behavior required for its intended function. In LPBF-fabricated components, manufacturing-induced characteristics, including surface roughness and porosity, may further affect wettability and its evolution with time.

To modify these surface characteristics, various surface engineering techniques have been developed and can be broadly categorized as chemical, mechanical, or combined treatments [26,27]. Chemical treatments, including etching [28], electrodeposition [29], graphene coating [30], TiO₂ coating [31], SiO₂ coating [32], sol-gel/dip-coating processes [33], spin coating [34], and spray coating [35], can alter surface chemistry, reduce surface energy, and promote hydrophobic or superhydrophobic behavior [36,37]. Depending on the treatment, these methods may also modify surface structure and improve corrosion resistance or provide other functional properties [38–42]. Mechanical treatments provide additional approaches for modifying surface conditions. Laser texturing and femtosecond-laser treatment can alter surface topography, whereas thermal processes such as annealing and aging can modify material and surface conditions to influence wettability [43–48]. These methods can generate micro- and nanoscale surface features that influence wetting behavior [49–51]. For instance, laser-treated SS surfaces have shown transitions from superhydrophilic to

superhydrophobic states after aging that have been associated with changes in surface chemistry [52,53]. Similarly, abrasive treatments such as sandblasting and steel shot blasting can modify surface finish and enhance coating adhesion, although their effectiveness in achieving superhydrophobicity alone is often limited [54–56]. Consequently, combined approaches that integrate surface roughening with low-surface-energy coatings have been investigated to promote hydrophobic or superhydrophobic behavior [54,57–59]. The prior studies therefore indicate that these surface engineering techniques can produce different wettability responses under specific material and processing conditions.

Despite extensive studies on SS surface treatments, further assessment is warranted regarding how selected post-processing treatments affect the wettability of LPBF-fabricated 17-4 PH SS surfaces in the context of TPMS-based condensation applications. TPMS geometry is defined primarily at the macroscale, whereas LPBF fabrication and subsequent surface treatments influence surface characteristics at smaller length scales. Furthermore, the curved and nonplanar surfaces of TPMS structures are not well suited to direct and repeatable CA measurements. Flat plate specimens manufactured from the same material using the same LPBF process therefore provide a practical basis for comparing surface treatment conditions without assuming that CA values measured on the planar specimens are identical to those of the corresponding TPMSs. Accordingly, the contribution of this study is not the development of a new hydrophobic coating, but the controlled comparison of thermal aging, three steel-shot grades, commercial hydrophobic coating, and selected treatment combinations on LPBF-fabricated 17-4 PH SS flat surfaces, together with a separate visual assessment of TPMS manufacturing irregularities. This design enables treatment-dependent wettability responses to be compared while explicitly recognizing that planar CA measurements cannot be transferred directly to curved TPMS surfaces.

The study investigates the fabrication of 17-4 PH SS TPMS structures by LPBF and evaluates selected post-processing treatments using flat plates manufactured from the same material by the same LPBF process. The fabricated TPMS structures are visually examined to document their overall condition and observed manufacturing irregularities. Thermal aging, steel shot blasting, hydrophobic coating, and selected combinations of these treatments are evaluated on the flat plates, whose planar surfaces facilitate controlled CA measurements. A preliminary comparison of steel shot sizes is included as part of the surface treatment evaluation. Surface wettability, including time-dependent wetting behavior, is assessed through deionized-water CA measurements using a ramé-hart goniometer. The objectives are to characterize the visible condition and identify manufacturing irregularities of the fabricated TPMS structures and to determine how the investigated post-processing treatments affect the wettability of flat 17-4 PH SS surfaces manufactured using the same LPBF process. The study provides manufacturing and wettability insights for future investigations of TPMS-based condensation surfaces in atmospheric water generation applications.

2. Materials and Methods

2.1. Specimen Design and Additive Manufacturing

Five TPMS geometries, Gyroid, Diamond, Lidinoid, SplitP, and Schwarz, were fabricated by Impac Systems Engineering (Company 1) (Temple, TX, USA) using LPBF [60]. Two sets of each TPMS geometry, corresponding to a total of ten TPMS structures, were produced. In addition, two square flat plate specimens, each measuring $20 \times 20 \times 6$ mm, were designed and fabricated using the same material and LPBF system.

The square flat plates were included to facilitate surface treatment evaluation and CA measurements. Direct and repeatable CA measurements on the TPMS structures were impractical because of their curved and nonplanar surfaces. Consequently, flat plates

were used to compare the wettability responses of the investigated treatment conditions. Although the flat plates were manufactured using the same material and LPBF process as the TPMS structures, the CA values obtained from the planar surfaces were not assumed to be identical to those of the corresponding curved TPMSs. The flat plates were used only to compare treatment-dependent wettability under planar measurement conditions. They were not treated as geometrically representative surrogates for the curved TPMSs, and the measured CA values were not extrapolated quantitatively to the TPMS structures.

All specimens were fabricated using a One Click Metal MPRINT LPBF system (Tamm, Baden-Württemberg, Germany) equipped with a 200 W fiber laser [49,60]. The build material was 17-4 precipitation-hardening stainless steel (17-4 PH SS; SAE Type 630, UNS S17400) [61]. This alloy was selected based on its combination of corrosion resistance, machinability, and cost relative to alternative materials considered for fabrication, including aluminum and copper.

Supplier Cost Comparison

Quotations for additive manufacturing services were obtained from two additional suppliers, Proto Labs, Inc., Maple Plain, MN, USA, and Xometry, Inc., North Bethesda, MD, USA (designated Company 2 [62] and Company 3 [63]). The nTop-generated Gyroid, Schwarz, and flat plate models were submitted to these suppliers for quotation. The Diamond, Lidinoid, and SplitP models were not included in the comparison because their files exceeded the vendors' upload limits. To maintain consistency, all quotations were requested for 17-4 PH SS.

Company 1 offered fabrication using LPBF with the One Click Metal system [64], whereas Companies 2 and 3 offered direct metal laser sintering (DMLS). The resulting quotations for the flat plate, Gyroid, and Schwarz specimens are summarized in Table 1. Company 1 was selected for fabrication based on the quoted costs presented in Table 1.

Table 1. Cost comparison of TPMS and flat plate specimens from three suppliers.

Item	Dimensions (mm)	Company 1 (Discounted Price, USD) [60]	Company 2 (USD) [62]	Company 3 (USD) [63]
Flat plate	20 × 20 × 6	\$10.31	\$219.92	\$352.54
Gyroid	40 × 40 × 30	\$163.88	\$588.84	\$880.53
Schwarz	40 × 40 × 30	\$153.02	\$750.89	\$887.38

2.2. Surface Treatment Design

The two LPBF-fabricated flat plates were used to compare thermal aging, steel shot blasting, hydrophobic coating, and selected combinations of these treatments. Each specimen was partitioned into four surface treatment regions, resulting in eight experimental conditions across the untreated and aged plates.

One plate was designated as the untreated plate and did not undergo thermal aging before blasting and coating were applied to the designated regions. The second plate was thermally aged before the corresponding blasting and coating treatments were applied. This arrangement enabled comparison of untreated, aged, blasted, coated, and combined treatment conditions.

2.2.1. Initial Cleaning

Before surface treatment, the flat plates were cleaned to remove grease and surface contaminants. Each plate was immersed in isopropyl alcohol for 10 min, rinsed with deionized (DI) water to remove residual solvent, and allowed to air dry under laboratory

conditions. Gloves were used when handling the cleaned plates to minimize subsequent contamination.

2.2.2. Thermal Aging

Thermal aging was performed at 480 °C for 1 h in a furnace. Following aging, the aged specimen and the specimen retained in untreated condition were immersed in ethanol for 10 min, allowed to dry, rinsed with DI water, and air dried before the final blasting and coating treatments. The thermally aged but otherwise untreated condition was designated A-0.

2.2.3. Preliminary Steel Shot Blasting Comparison

A preliminary experiment was conducted to compare three spherical steel shot grades: S-110 [65], S-230 [66], and S-330 [67]. Their nominal particle sizes and reported surface-finish classifications are provided in Table 2.

Table 2. Steel shot grades evaluated in the preliminary blasting experiment.

Steel Shot Grade	Approximate Shot Size (mm)	Surface Finish Type
S-110	0.28	Smooth
S-230	0.58	Medium
S-330	0.84	Medium

Each shot grade was applied separately to designated side surface regions on the untreated and aged plates. The target surface was exposed while the remaining surfaces were protected using multiple layers of tape and secured with clamps. Blasting was performed for 20 s at a compressed-air pressure of 85 psi, with a nozzle-to-surface distance of approximately 1 in. The blasting arrangement, employing a NANPU sandblaster gun [68], is shown in Figure 1.



Figure 1. Steel shot blasting in an enclosure using a NANPU sandblaster gun connected to an 85 psi compressed-air supply.

The 85 psi pressure was selected to limit the severity of abrasive impact because the intended TPMS application includes thin structural features that could be vulnerable to damage at higher blasting pressures. The surface regions produced using the three shot grades were subsequently evaluated by CA measurement. The shot grade producing the highest CA values under the investigated conditions was selected for the subsequent treatment study.

Based on the preliminary CA comparison, S-330 steel shot was used for the subsequent treatment conditions. For this stage, the designated surface regions of the untreated and aged plates were blasted for 30 s at 85 psi, with the nozzle maintained approximately 1 in.

from the surface. Tape and clamps were used to isolate the intended treatment regions and protect the adjacent surfaces.

2.2.4. Treatment Conditions and Region Assignment

The surface treatment design produced eight surface conditions: untreated, blasted, coated, blasted and coated, aged, aged and blasted, aged and coated, and aged, blasted, and coated. The surface treatment region layout is presented in Figure 2, and the corresponding condition codes are listed in Table 3.

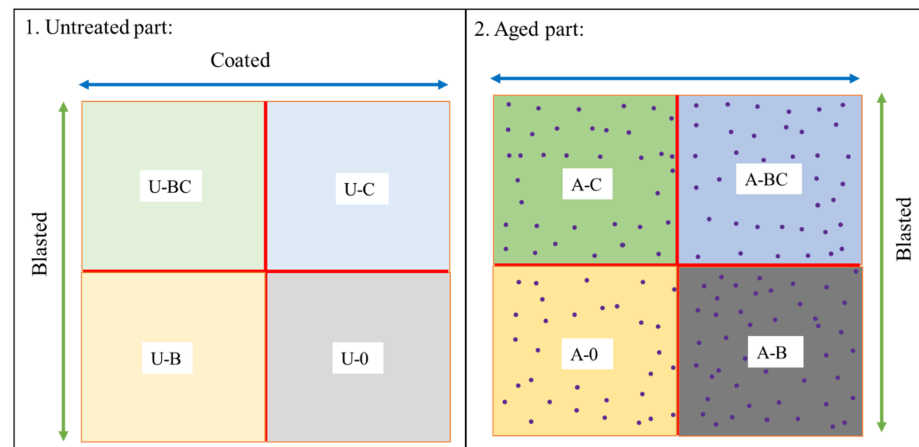


Figure 2. Surface treatment layout for (1) the untreated part and (2) the aged part.

Table 3. Surface treatment conditions and code assignments.

Treatment Condition	Code	Description
Untreated	U-0	LPBF-fabricated surface without post-processing
Blasted	U-B	Untreated surface subjected to steel shot blasting
Coated	U-C	Untreated surface subjected to hydrophobic coating
Blasted + Coated	U-BC	Untreated surface subjected to steel shot blasting followed by hydrophobic coating
Aged	A-0	Thermally aged surface without post-processing
Aged + Blast	A-B	Thermally aged surface subjected to steel shot blasting
Aged + Coated	A-C	Thermally aged surface subjected to hydrophobic coating
Aged + Blast + Coated	A-BC	Thermally aged surface subjected to steel shot blasting followed by hydrophobic coating

2.2.5. Hydrophobic Coating Application

A commercial two-step Rust-Oleum hydrophobic coating system was applied to the designated surface regions [69]. Before coating, the applicable surfaces were cleaned using the procedure described in Section 2.2.1. The uncoated regions were masked with cardboard to limit coating deposition outside the intended treatment areas.

For the first step, the base-coat container was shaken vigorously for 1 min after the mixing ball became audible and was shaken periodically during application. One base coat was applied from a distance of approximately 6 in. Because each treatment region was approximately $10 \times 10 \text{ mm}^2$, a single coat was used. The base coat was allowed to dry for 40 min before application of the topcoat.

For the second step, the topcoat container was shaken for 1 min after the mixing ball became audible and was shaken periodically during application. The topcoat was applied from a distance of approximately 6–12 in. Two light passes were applied in perpendicular directions, one from side to side and one from top to bottom, while avoiding excessive

wetting of the surface. After drying for 15 min, two additional perpendicular passes were applied. The coated surfaces were cured for 24 h before exposure to water.

2.3. CA Measurement

Surface wettability was evaluated using a ramé-hart goniometer equipped with DropImage V3.1808 software and a computer-controlled automatic dispenser [70]. DI water was used as the test liquid. The measurement system is shown in Figure 3.

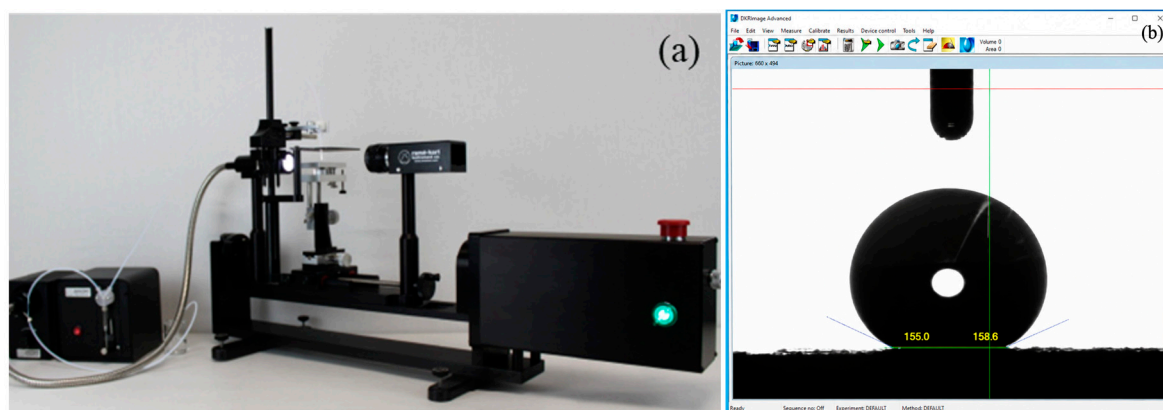


Figure 3. (a) ramé-hart goniometer and (b) automated CA measurement using DropImage software [70].

2.3.1. Time-Dependent Static CA and Droplet-Volume Evaluation

The time-dependent wettability of the untreated flat plate was evaluated using DI-water droplets with volumes of 1.0, 2.5, 5.0, 7.5, and 10.0 μL . For measurements on the top surface, CA values were recorded at 1 min intervals from initial deposition (0 min) to 4 min. A 2.5 μL droplet was used for the side-surface measurement, for which CA values were recorded from 0 to 2 min.

These measurements were used to examine changes in CA with time and to compare the wetting behavior associated with the investigated droplet volumes. The aged surface was also evaluated to determine its wettability condition. The measurements represent time-dependent static CA observations after droplet deposition. Advancing and receding CA, CA hysteresis, sliding or roll-off angle, droplet-shedding behavior, and repeated-wetting durability were not measured.

2.3.2. CA Evaluation Following the Preliminary Blasting Study

For each S-110, S-230, and S-330 blasted surface region, three 5 μL DI-water droplets were dispensed. Thirty CA measurements were recorded for each droplet using the DropImage software. The recorded minimum and maximum values were used to construct the estimated box-and-whisker representation reported in Section 3.

2.3.3. CA Evaluation of the Eight Treatment Conditions

CA measurements were performed on each of the eight treatment regions defined in Figure 2 and Table 3. Thirty measurements were recorded for each condition. A 5 μL DI-water droplet was used for the untreated, aged, and blasted conditions. A 15 μL droplet was used for the coated surfaces because the smaller droplets could not be dispensed onto those surfaces under the measurement conditions.

The mean CA obtained for each treatment region was used to compare the wettability responses of the eight surface conditions. The present study was limited to visual examination and CA measurement. Quantitative surface morphology, roughness, porosity, coating thickness, and chemical composition were not characterized; consequently,

morphology- and chemistry-based mechanisms were not evaluated. Accordingly, no morphology- or chemistry-based mechanism is proposed for the measured differences among the treatment conditions.

3. Results and Discussion

3.1. Fabrication and Visual Assessment of TPMS Structures

Five TPMS geometries, Schwarz, Gyroid, Diamond, Lidinoid, and SplitP, were selected from the previously evaluated configurations [71]. The selected lattice thicknesses and cell sizes are listed in Table 4. These geometries were fabricated to provide physical TPMS structures for the intended application context, while two flat plates were produced for the surface treatment and CA investigations. Because the curved and nonplanar TPMS surfaces were not suitable for direct and repeatable CA measurements, the wettability results presented in this study were obtained from the flat plates rather than from the TPMS structures.

Table 4. TPMS configurations selected for LPBF fabrication [71].

	Cell Type, C	Sensitivity/Weight	Lattice Thickness, L(mm)	Cell Size, X (mm ³)
1	Schwarz	SA/V = 0.75; ΔT = 0.25	1	10
2	Gyroid	SA/V = 0.75; ΔT = 0.25	2	12
3	Diamond	SA/V = 0.75; ΔT = 0.25	1.5	12
4	Lidinoid	SA/V = 0.75; ΔT = 0.25	1.5	12
5	SplitP	SA/V = 0.75; ΔT = 0.25	2	12

The 17-4 PH SS TPMS structures and flat plates were successfully fabricated by LPBF through Impac Systems Engineering. Representative top and isometric views of the received components are shown in Figure 4. Visual examination indicated that the overall TPMS geometries were reproduced, although localized manufacturing irregularities were present. These observations included burnt or partially fused material near some edges, distortion of certain thin boundary features, and differences in surface appearance among the top, side, and bottom faces.

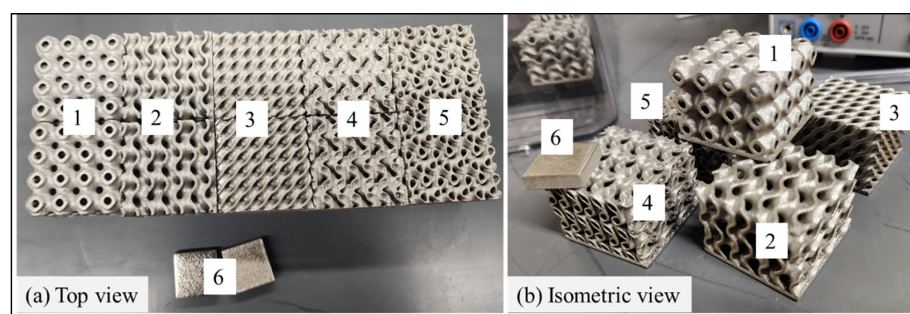


Figure 4. LPBF-fabricated 17-4 PH TPMS structures shown in (a) top and (b) isometric views: 1. Schwarz; 2. Gyroid; 3. Diamond; 4. Lidinoid; 5. SplitP; and 6. flat plate.

The fabrication results demonstrate that the selected TPMS geometries could be physically produced using the employed LPBF process. However, the localized irregularities also indicate that producing complex structures does not necessarily result in uniform surface condition or geometric fidelity across all features. Because no quantitative dimensional inspection, porosity measurement, or surface-roughness analysis was performed, the present assessment is limited to the visible condition of the fabricated structures and the explanations provided through consultation with the manufacturer.

3.2. Wettability of the Untreated and Surface-Treated Plates

3.2.1. Time-Dependent Wettability of the Untreated Plate

Figure 5 presents the time-dependent static CA measurements obtained from the untreated flat plate using DI-water droplet volumes ranging from 1.0 to 10.0 μL . Measurements were obtained from the top surface for all five droplet volumes, whereas a 2.5 μL droplet was used for the side-surface measurement shown in Figure 5f. The measured CA values remained below 90° , identifying the untreated LPBF-fabricated surface as hydrophilic under the investigated conditions.

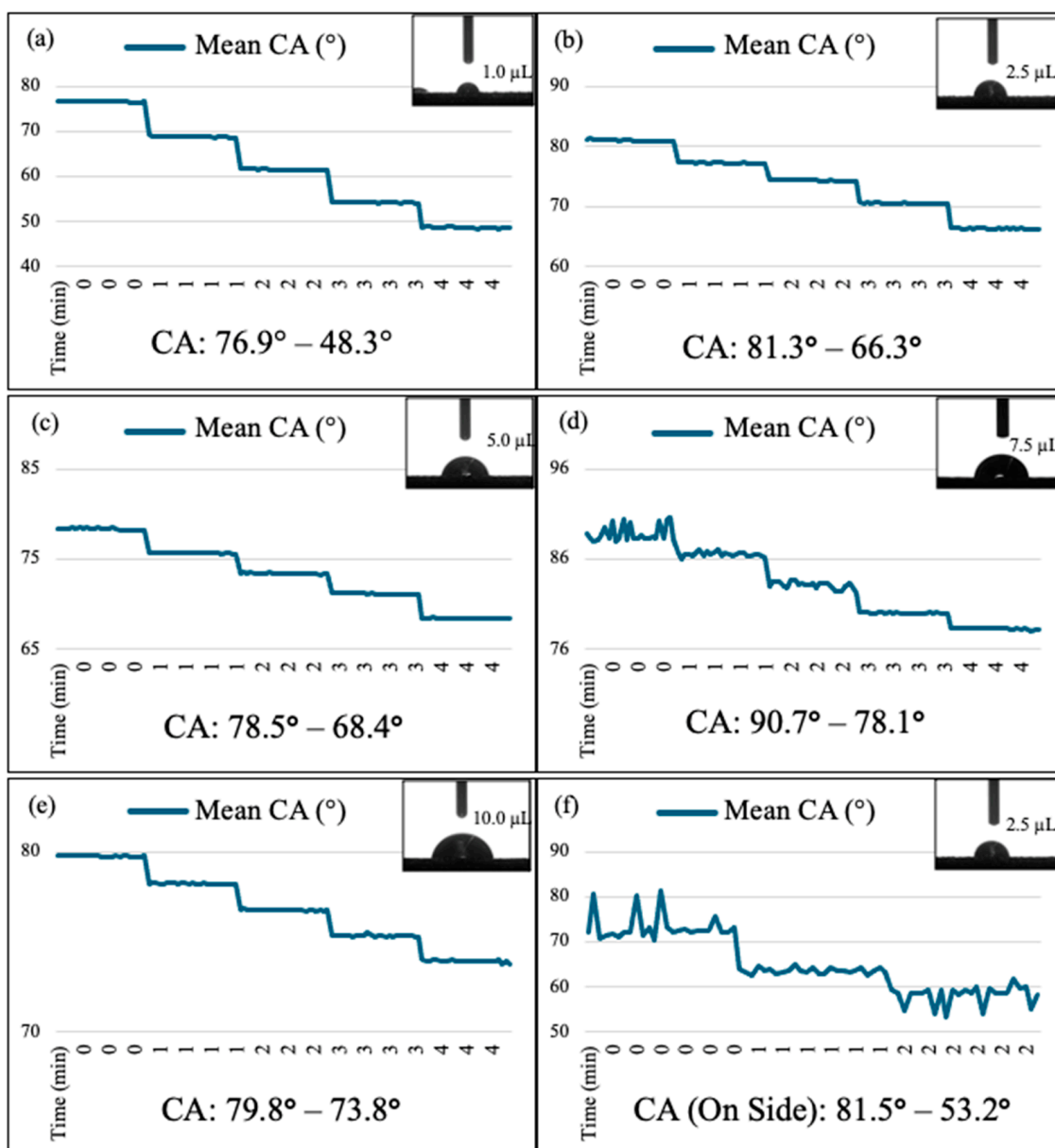


Figure 5. Time-dependent CA measurements for different DI-water droplet volumes on the (a–e) top and (f) side surfaces of the untreated flat plate. Insets show the droplet volumes used for the respective measurements.

For each droplet volume, the highest CA was generally recorded immediately after deposition, followed by a progressive decrease with time. Measurements on the top surface were obtained from 0 to 4 min, whereas the side-surface measurements were obtained from 0 to 2 min. The observed reduction in CA indicates increasing wetting of

the untreated surface during the measurement period. Continued observation showed complete spreading of the droplets between approximately 8 and 10 min.

The rate of the observed CA decrease varied with droplet volume. For example, the 1.0 μL droplet reached 48.3° after 4 min, whereas the 2.5 μL droplet reached 66.3° over the same period, as shown in Figure 5a,b. Thus, the smaller droplet exhibited a more rapid decrease in CA in this comparison. Nevertheless, because the measurements involved different droplet volumes and surface locations and no statistical test of droplet-volume effects was reported, these observations should not be interpreted as establishing a general quantitative relationship between droplet volume and CA. Consistent with the prior literature cited in the original work [72], droplet volume did not change the overall classification of the untreated surface as hydrophilic.

The horizontal segments and stepwise changes visible in the measurement curves result from the automated acquisition procedure used by DropImage software. Minor peaks and valleys, particularly in Figure 5d,f, were associated with automatic adjustment of the contact-line position during image analysis. These features should therefore be interpreted as measurement-related variations rather than as separate wetting transitions.

The time-dependent decrease in CA is consistent with progressive interaction between the water droplet and the LPBF-fabricated surface. The original observations associated this behavior with manufacturing-induced porosity and surface texture. However, because porosity, roughness, capillary infiltration, and surface chemistry were not independently measured in this study, their individual contributions cannot be separated. The results directly establish time-dependent wetting of the untreated surface but do not independently verify the mechanism responsible for that behavior. Measurements on the aged surface similarly yielded CA values within the hydrophilic regime.

3.2.2. Preliminary Comparison of Steel Shot Blasting

The effects of S-110, S-230, and S-330 steel shot blasting on untreated and aged surfaces are shown in Figure 6. Among the three blasting media, S-330 produced the highest observed CA values for both plate conditions. For the untreated surface blasted with S-330, one of the three evaluated droplets produced CA measurements above 90° , whereas the remaining measurements did not indicate a consistent transition of the blasted surface to hydrophobic behavior.

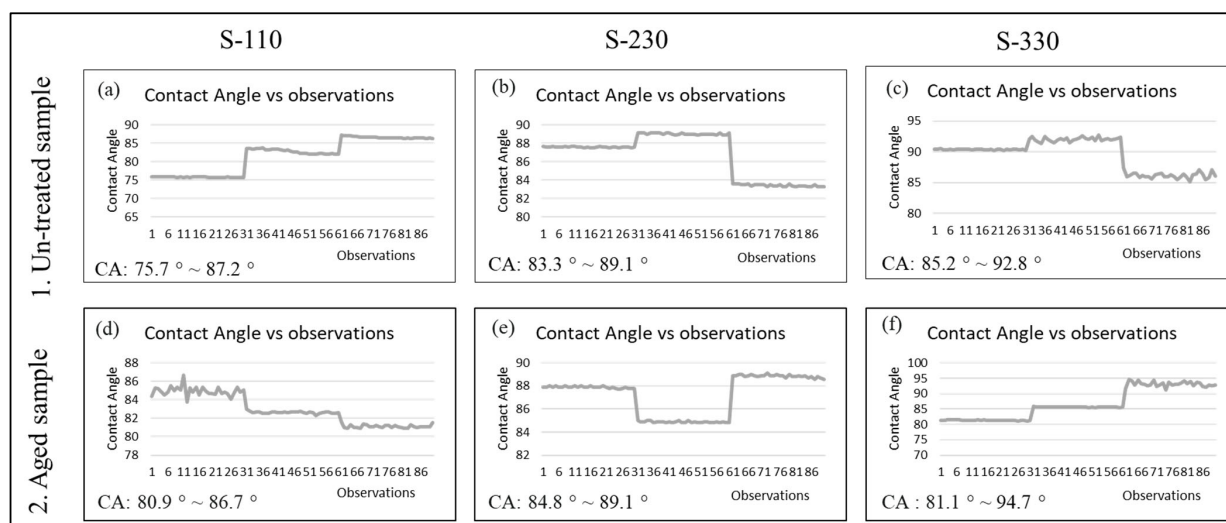


Figure 6. CA measurements for untreated and aged surfaces after blasting with different steel shot grades: S-110, (a,d); S-230, (b,e); and S-330, (c,f).

Blasting with S-110 and S-230 resulted in lower CA values than those obtained with S-330. The resulting surfaces remained hydrophilic under the investigated conditions. Although these differences demonstrate that the selected shot size affected the measured wetting response, the experiment did not include quantitative surface-roughness measurements. Consequently, the differences cannot be attributed conclusively to smoother or rougher surfaces, nor can a specific roughness–wettability relationship be established from the CA measurements alone.

Figure 7 presents the observed minimum–maximum CA ranges for the evaluated blasting conditions. The figure is useful for visualizing the observed ranges; however, because it was constructed from extrema rather than a complete statistical distribution, it should not be interpreted as a conventional inferential box-and-whisker analysis. No statistical significance is claimed for the differences among the blasting conditions.

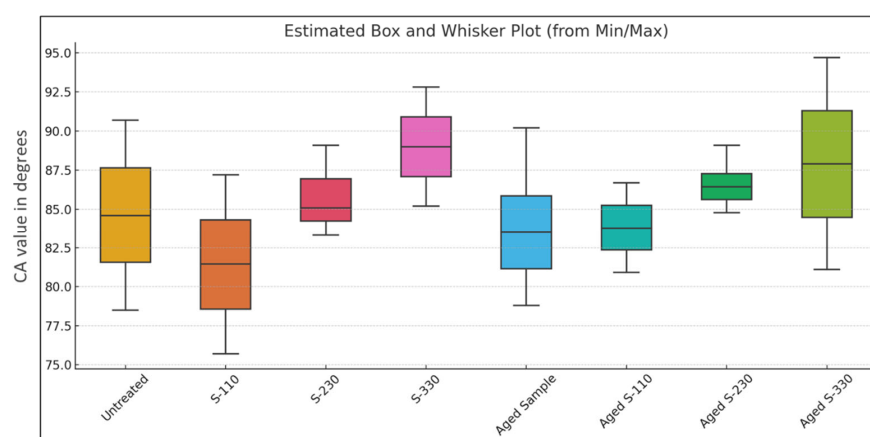


Figure 7. Observed minimum–maximum CA ranges for untreated and aged surfaces before and after blasting with S-110, S-230, and S-330 steel shot.

Within these limitations, the plotted ranges confirm that S-330 produced the highest CA values among the three shot grades under the investigated blasting parameters. S-330 was therefore selected for the subsequent treatment study. This selection identifies the most suitable medium among the tested shot grades and conditions; it does not establish S-330 as universally optimal for LPBF-fabricated 17-4 PH SS.

3.2.3. Appearance of the Treated Surface Regions

Following the preliminary comparison, S-330 steel shot was used for the final blasting conditions. The untreated and aged plates were divided into treatment regions representing untreated or aged, blasted, coated, and blasted-plus-coated conditions, as defined in Figure 2 and Table 3. Photographs of the resulting treatment maps are presented in Figure 8.

The aged region (A-0) appeared darker than the corresponding untreated region (U-0), consistent with visible surface changes following furnace exposure. The blasted regions (U-B and A-B) exhibited a dark gray appearance that differed from the corresponding unblasted surfaces. Differences in visible texture were also observed between U-B and A-B. These observations establish changes in appearance but do not, by themselves, demonstrate changes in hardness, roughness, oxide composition, or other material properties because those characteristics were not independently measured.

Application of the two-step commercial coating also altered the visible appearance of the selected regions. The first coating step produced a gray base layer, whereas the second step produced a visually clear top layer. The final appearances of the four coated regions, U-C, U-BC, A-C, and A-BC, were broadly similar by visual inspection, irrespective of

whether thermal aging or blasting preceded coating. Visual similarity, however, should not be interpreted as evidence of identical coating thickness, coverage, adhesion, or durability, because these properties were not evaluated.

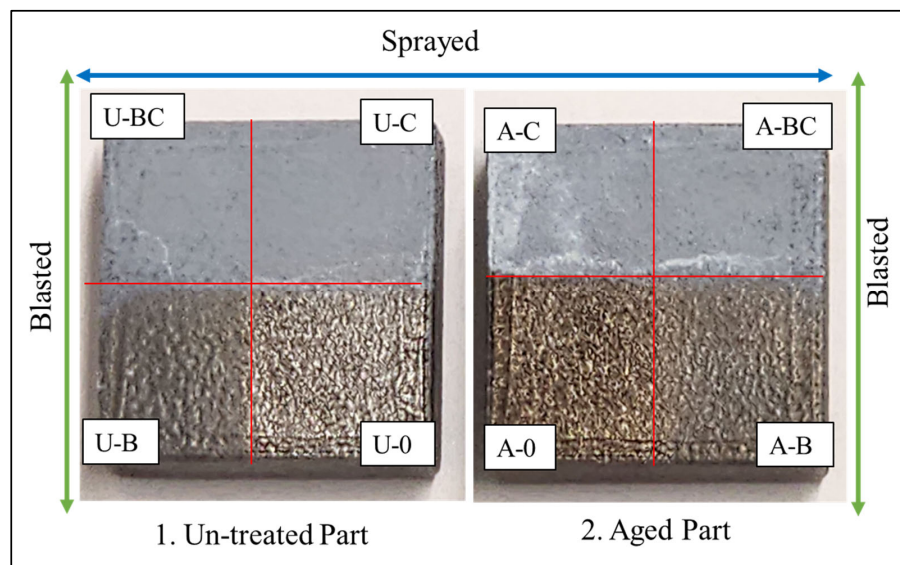


Figure 8. Surface treatment map of the untreated and aged flat plates after S-330 blasting and application of the two-step hydrophobic coating. Red lines denote the boundaries of the separated regions.

3.2.4. Wettability of the Eight Treatment Conditions

The CA values obtained from the eight treatment regions are summarized in Figure 9. The uncoated regions, U-0, U-B, A-0, and A-B, remained within the hydrophilic range, with CA values near 90° or below. S-330 blasting produced only a modest change relative to the corresponding unblasted condition. Specifically, blasting increased the CA of the untreated plate by approximately 2° but decreased the CA of the aged plate by approximately 5°.

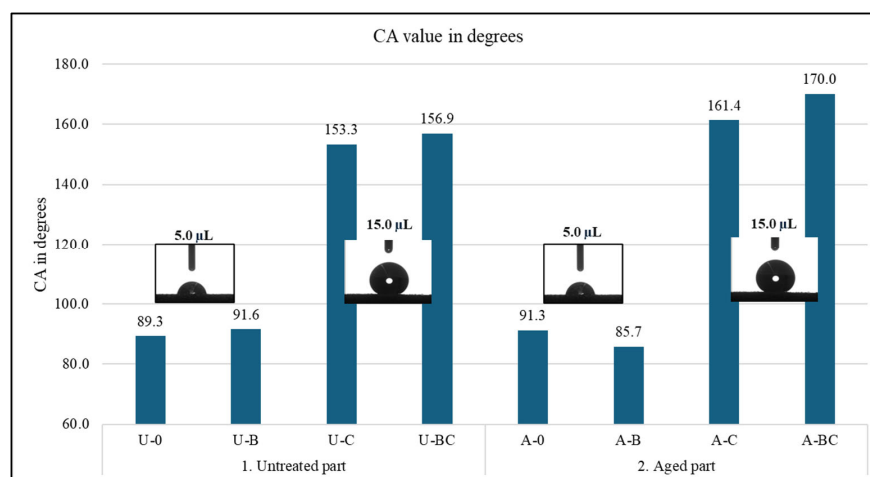


Figure 9. Mean CA values for the treatment regions on (1) the untreated part and (2) the aged part. 5 µL droplets were used for U-0, U-B, A-0, and A-B; whereas 15 µL droplets were used for U-C, U-BC, A-C, and A-BC.

These opposing responses indicate that the effect of blasting depended on the initial plate condition under the investigated parameters. The original interpretation proposed that thermal aging may have altered the surface condition and that retained oxide layers or other surface products could have influenced the response to blasting. This explanation remains plausible but unverified because surface composition and oxide condition were not

analyzed. Accordingly, the present results support a condition-dependent CA response to blasting, but they do not establish the chemical mechanism responsible for that difference.

All four coated regions, U-C, U-BC, A-C, and A-BC, produced CA values exceeding 150° , with measured values ranging from approximately 153° to 170° . These values place the coated surfaces within the superhydrophobic CA range under the measurement conditions used. A 15 μL droplet was required for CA measurements on the coated regions because the 5 μL droplets used for the uncoated conditions could not be dispensed onto those surfaces using the available apparatus. Because different droplet volumes were used for coated and uncoated regions, the comparison should be interpreted principally in terms of the substantial difference in wettability classification rather than as a strictly volume-controlled comparison of CA magnitude.

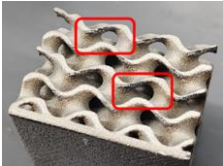
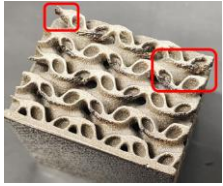
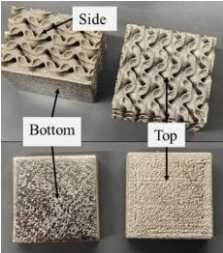
The coated-only conditions and the blasted-plus-coated conditions all exhibited superhydrophobic CA values. Therefore, the data show that application of the commercial coating was associated with the transition to superhydrophobic behavior, regardless of whether the surface had been thermally aged or blasted beforehand. The results do not demonstrate that prior S-330 blasting was necessary to achieve superhydrophobicity. Likewise, because coating chemistry, surface structure, thickness, adhesion, and air entrapment were not characterized, a specific Cassie-Baxter mechanism or hierarchical surface structure cannot be confirmed from the CA data alone.

3.3. Discussion

3.3.1. Manufacturing Irregularities in the TPMS Structures

The LPBF process produced all five selected 17-4 PH SS TPMS geometries, and the overall forms of the structures were retained. Nevertheless, localized irregularities, including burnt edges, distorted boundary features, and variations in surface finish, were visible. Table 5 summarizes these observations and the explanations provided through consultation with the manufacturer.

Table 5. Manufacturing irregularities and explanation with proposed consideration.

Irregularities		Images	Explanation with Proposed Consideration
1	Burnt edges		Localized burning or fused powder was observed near unsupported overhangs. Support removal would be difficult within the TPMS geometry, and alternative overhang profiles could reduce this effect. This modification was not evaluated in the present study.
2	Distorted structure		Distortion occurred in thin, unsupported boundary features. Extending the lattice boundary by approximately $\frac{1}{4}$ – $\frac{1}{2}$ in. and subsequently removing the extension by wire EDM or machining could improve dimensional accuracy. This proposed approach was not experimentally evaluated.
3	Difference in surface finish		Differences among the bottom, top, and side surfaces were associated with build orientation and post-build handling. The bottom surface was separated from a 3 mm sacrificial layer and mechanically finished, whereas the top and side surfaces retained different visual features associated with the LPBF build sequence.

The burnt appearance was observed primarily near unsupported overhangs. According to the manufacturer, localized accumulation and fusion of powder can occur at such features. Supports could potentially be introduced for certain overhang angles; however, removing supports from the internal and curved regions of TPMS structures would be difficult. The manufacturer suggested that alternative overhang profiles, including more angular rather than rounded features, could reduce this issue. This proposed modification was not fabricated or evaluated in the present study and should therefore be regarded as a potential design consideration rather than a demonstrated remedy.

Distortion was also observed in thin external features near the lattice boundary. The manufacturer associated this behavior with the limited rigidity and unsupported condition of these features during fabrication. Extending the lattice boundary and subsequently removing the added material by wire electrical discharge machining or conventional machining was suggested as a potential mitigation strategy. Because no redesigned specimens were manufactured, the present study does not establish whether this approach would eliminate distortion or improve dimensional accuracy.

Differences in surface appearance were evident among the bottom, top, and side faces. The manufacturer indicated that each component was connected to the substrate through an approximately 3 mm sacrificial support layer and subsequently removed using a bandsaw. Mechanical finishing with a Scotch-Brite wheel was used on the bottom surface after removal, producing a smoother and more reflective appearance. The top surface represented the final layers of the build, whereas the side surfaces retained the visible layer-wise texture of the LPBF process. These observations help explain the qualitative differences in appearance, but quantitative surface-finish differences were not measured.

The observations demonstrate that TPMS geometry and LPBF fabrication are associated with localized manufacturing challenges. However, because only visual examination was performed and only one fabrication process and supplier were evaluated, the results do not define the general printability of each TPMS geometry or quantify the effects of geometry on defect formation.

3.3.2. Time-Dependent Wetting Behavior

The untreated LPBF-fabricated flat plate exhibited hydrophilic behavior and a progressive reduction in CA after droplet deposition. The initial CA decreased from approximately 81° to values as low as 48° during the first 4 min, with complete spreading observed after approximately 8–10 min. This behavior indicates that the untreated surface did not maintain a stable initial CA over time.

The original work associated the observed wetting transition with the porous and textured condition of the LPBF-fabricated material. Such an interpretation is consistent with the possibility that manufacturing-induced surface features promote liquid spreading. Nevertheless, the present study did not quantify porosity, surface roughness, surface energy, or infiltration behavior. The results therefore establish time-dependent wetting but do not distinguish among capillary infiltration, surface heterogeneity, evaporation, roughness, chemical condition, or other possible contributions.

Droplet volumes from 1.0 to 10.0 μL did not alter the overall hydrophilic classification of the untreated surface, although the measured rate of CA reduction varied among the investigated volumes. The observation that droplet volume did not produce a change in the overall surface classification is consistent with the cited literature [72]. A more definitive assessment of droplet-volume dependence would require controlled replication and statistical comparison, which were not reported in the present work. Accordingly, the measured CA decrease should be reported as time-dependent wetting behavior rather than as evidence of a specific pore-infiltration, roughness-driven, or Wenzel wetting mechanism.

Because advancing and receding CA, CA hysteresis, sliding angle, droplet departure, and repeated-wetting durability were not evaluated, the present results characterize static wettability and its temporal evolution after deposition rather than dynamic droplet mobility relevant to condensation-surface performance.

3.3.3. Effects of Thermal Aging and Steel Shot Blasting

The preliminary blasting experiment demonstrated that the selected steel shot grade influenced the measured CA. S-330 produced the highest values among the evaluated media, whereas S-110 and S-230 generally produced lower values. This result justified the use of S-330 for the subsequent treatment conditions.

Despite the relatively higher CA obtained using S-330, the blasting treatment alone did not produce consistent hydrophobic behavior. The untreated and aged blasted regions remained hydrophilic in the final treatment comparison. Shot blasting should therefore be interpreted as producing a modest, condition-dependent modification of wettability rather than as independently generating a hydrophobic surface.

The direction of the blasting response differed between the untreated and aged plates: CA increased slightly after blasting the untreated surface but decreased after blasting the aged surface. Thermal exposure visibly changed the aged plate, and such changes may have affected its response to blasting. However, the original explanation involving residual oxides or contaminants was not verified by compositional analysis. The present findings support an interaction between initial surface condition and blasting response, but further surface characterization would be required to identify the responsible mechanism.

3.3.4. Effect of the Hydrophobic Coating

The largest change in wettability occurred after application of the commercial coating. All coated regions exhibited CA values between approximately 153° and 170°, whereas the untreated, aged, and blasted-only regions remained hydrophilic. The coating therefore produced superhydrophobic CA values under the investigated measurement conditions.

Importantly, superhydrophobic values were obtained for both coated-only and blasted-plus-coated conditions. The data consequently do not show that shot blasting was required before coating, nor do they establish that the combined treatment was superior to coating alone. Such a determination would require replicated statistical comparisons and additional evaluation of properties such as coating coverage, adhesion, durability, and long-term wetting stability.

The substantial increase in CA is consistent with the intended function of the commercial hydrophobic coating. Nevertheless, the study did not characterize the chemical composition or morphology of the deposited layers. The CA measurements directly support the classification of the coated regions as superhydrophobic but do not independently resolve the physical or chemical origin of that behavior. Within the investigated conditions, the principal treatment-related finding is that both coated-only and blasted-plus-coated regions reached the superhydrophobic CA range; therefore, the results do not demonstrate that steel-shot blasting was required before coating. In addition, the opposite CA responses of the untreated and aged surfaces to S-330 blasting indicate that the initial surface condition influenced the measured blasting response, although the mechanism responsible for this difference was not determined.

The results show that the selected 17-4 PH SS TPMS structures could be fabricated by LPBF, although visible localized irregularities were present. The corresponding untreated flat LPBF plate exhibited hydrophilic and time-dependent wetting behavior. Steel shot blasting modified the measured CA, with S-330 producing the highest values among the evaluated media, but blasting alone did not consistently produce hydrophobicity. In

contrast, application of the commercial coating produced superhydrophobic CA values across all coated treatment conditions.

The present study does not evaluate atmospheric water-generation effectiveness. No condensation rate, collected-water mass, collection area, air temperature, relative humidity, dew-point condition, or surface temperature data were obtained. The results also do not establish droplet-shedding behavior, coating durability, or equivalence between the wettability of flat plates and curved TPMSs. Those properties require direct evaluation before the treatment results can be extended to the functional performance of TPMS-based atmospheric water generation systems.

4. Conclusions

This study investigated the LPBF fabrication of five 17-4 PH SS TPMS geometries and the wettability response of corresponding flat plates subjected to thermal aging, steel-shot blasting, hydrophobic coating, and selected combinations of these treatments. The selected TPMS structures were successfully fabricated, with their overall geometries retained; however, visual examination identified localized irregularities, including burnt edges, distortion of thin boundary features, and differences in surface appearance. These observations indicate that curved features, thin sections, and unsupported regions require consideration when designing TPMS structures for LPBF. Potential design modifications, such as sacrificial boundary extensions followed by material removal, were identified through consultation with the manufacturer but were not experimentally evaluated in this study.

The untreated LPBF-fabricated 17-4 PH SS surface exhibited hydrophilic and time-dependent wetting behavior. The CA decreased from an initial value of approximately 81° to values as low as 48° within 4 min, and complete wetting was observed within approximately 8–10 min. Although this behavior may be associated with manufacturing-induced surface characteristics, the individual contributions of porosity, surface roughness, surface chemistry, and liquid infiltration were not independently characterized. Among the three steel-shot grades evaluated, S-330 produced the highest CA values under the investigated blasting conditions. Nevertheless, shot blasting alone produced only modest and condition-dependent changes in wettability: the untreated and aged blasted regions remained hydrophilic, and the direction of the CA change differed between the two plate conditions.

Application of the commercial hydrophobic coating produced the largest change in wettability, with CA ranging from approximately 153° to 170° across all coated regions. Superhydrophobic CA values were obtained both with and without prior steel-shot blasting and irrespective of thermal aging. Therefore, the results demonstrate that the coating was associated with superhydrophobic behavior under the investigated conditions but do not establish that prior blasting was necessary. Overall, the study identifies the visible manufacturing characteristics of LPBF-fabricated 17-4 PH SS TPMS structures and demonstrates how the selected post-processing treatments affected the wettability of corresponding flat surfaces. These findings provide manufacturing and wettability insights for future investigations of TPMS-based condensation surfaces in atmospheric water generation applications.

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