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COMPARISON OF VIBRATIONAL TUMBLING AND ELECTROLYTIC POLISHING ON SURFACE ROUGHNESS PARAMETERS OF ADDITIVELY MANUFACTURED INCONEL 718 ALLOY

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Abstract

This study delves into the comparative analysis of vibrational tumbling and electrolytic polishing, two distinct surface finishing techniques, on the surface roughness parameters of additively manufactured Inconel 718 alloy. Surface roughness significantly impacts the functionality of components, especially in aerospace and automotive applications where Inconel 718 superior mechanical properties are sought after. Vibrational tumbling relies on mechanical abrasion, while electrolytic polishing utilizes chemical processes, offering different pathways to attain smoother surfaces. Three samples were individually subjected to vibrational tumbling, electrolytic polishing and combination of both to determine its effects on surface roughness parameters Sa, Sq, Sp and Sv, evaluated via surface profilometry. Surface wettability was also determined for all the formed surfaces to evaluate the surface nature and functionality. The results indicated that the areal roughness parameter values ranged from Sa = 5.68 to 3.38 µm. The maximum surface height parameter varied from Sz = 53.36 to 32.44 µm, while the maximum valley height Sv ranged from 29.418 to 18.026 µm, and the maximum peak height Sp varied from 23.942 to 14.418 µm across all the printed samples. The findings showed a decrease of 32%, 12% and 42% for vibrational tumbling, electrolytic polishing and combination of both, respectively in the surface roughness values from as built samples. Further, the surface wettability results showed increase in the hydrophilic nature of the surface for each treated surface. The results furnish valuable insights into the efficacy of each method in enhancing surface quality, aiding in informed selection of the optimal surface finishing technique for additively manufactured Inconel 718 components.

Keywords:
Additive Manufacturing, Selective Laser Melting, Inconel 718, Vibrational tumbling, Electrolytic polishing, Contact angle measurements

1 INTRODUCTION

Additive Manufacturing (AM) has revolutionized modern manufacturing, offering unparalleled design flexibility, reduced material wastage, and rapid prototyping capabilities. Among the array of AM techniques, Selective Laser Melting (SLM) has emerged as a prominent method for crafting intricate metal components, especially utilizing high-performance alloys like Inconel 718. Renowned for its superb mechanical properties, corrosion resistance, and ability to withstand high temperatures, Inconel 718 finds extensive application in aerospace, automotive, and energy sectors where demanding environments prevail (Dwivedi et al. 2023; Srivastava et al. 2023).

However, despite the precision and complexity achievable with SLM, concerns persist regarding surface quality. The layer-by-layer nature of SLM fabrication often yields surface irregularities such as porosity, stair-stepping, and roughness, compromising both functional performance and structural integrity (Anand & Das, 2022; Měsíček et al., 2022). Consequently, effective post-processing techniques are imperative to refine the surface finish of additively manufactured Inconel 718 components (Mesicek et al., 2021).

Inconel 718, a superalloy primarily composed of nickel, is highly valued for its capacity to retain mechanical strength at elevated temperatures between 600°C and 750°C (Hajnys et al., 2020). Using SLM to produce Inconel 718 preserves its high-temperature strength and resistance to oxidation and fatigue. However, it can result in distinct microstructures, anisotropy, surface roughness, and internal porosity. Therefore, it is crucial to improve surface smoothness, decrease porosity, refine the microstructure, and control residual stresses in SLM-fabricated Inconel 718 components (Ross et al., 2024). These issues can be addressed with post-processing techniques.

There are many post-processing techniques such as machining, polishing, centrifugal tumbling, vibrational tumbling, laser micro machining, chemical polishing, electrolytic polishing, sand blasting, rolling, shot peening, and hybrid treatments (Kozior et al., 2023). Two commonly used post-processing methods for improving surface roughness in SLM-produced parts are vibrational tumbling and electrolytic polishing. Vibrational tumbling involves subjecting components to mechanical agitation within a tumbling chamber filled with abrasive media, effectively eradicating surface imperfections and yielding a smoother finish. Conversely, electrolytic polishing employs an electrochemical process to selectively dissolve surface irregularities, resulting in a polished surface with reduced roughness.

A previous study showed that centrifugal tumbling markedly improves the surface roughness of AlSi10Mg printed samples compared to vibratory tumbling, reaching the lowest average Ra of 0.30 µm. These results indicate that centrifugal tumbling is a more cost-effective method for achieving efficient surface finishing (Mechali et al., 2024). A decrease in surface roughness Ra from 6.05 µm to 3.66 µm was observed following electropolishing of LPBF Inconel 718 samples was shown in another study (Baicheng et al., 2017). Despite sharing the objective of enhancing surface quality, vibrational tumbling and electrolytic polishing diverge in mechanisms and outcomes, leading to distinct surface characteristics in SLM-produced Inconel 718 components(Sternadelova et al., 2024). Understanding the comparative impacts of these post-processing techniques on surface roughness parameters is pivotal for optimizing the manufacturing process and ensuring the desired functional properties of AM parts.

This study endeavors to investigate and compare the effects of vibrational tumbling and electrolytic polishing on the surface roughness parameters of additively manufactured Inconel 718 alloy components fabricated via the SLM method. Samples were subjected individually to vibrational tumbling, electrolytic polishing and combination of both. Surface roughness parameters Sa, Sz, Sp and Sv were evaluated for each sample to determine the effect of post-processing. Further surface wettability was also carried out to determine the change in the surface functionality in terms of hydrophilicity. The insights gleaned from this research will drive advancements in surface finishing methodologies for SLM-based additive manufacturing and facilitate the formulation of tailored post-processing protocols for Inconel 718 alloy components.

2. Materials and method

Inconel 718 powder with powder grain size ranging from 15 to 45 µm was used for the present study. Figure 1 shows a scanning electron microscopy (SEM) image of the used Inconel 718 powder.

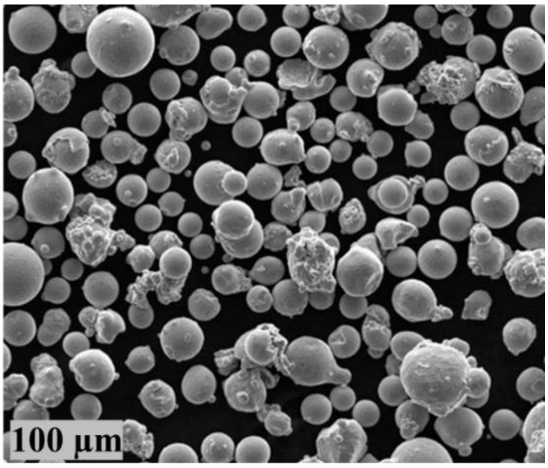


Fig. 1. SEM images depicting the particle shapes of the Inconel 718 powder.

In this current study, the LPBF technique is employed along with Inconel 718 powder material to produce a model in a stripe shape. The chemical composition of the used Inconel 718 powder is shown in Figure 2. The printing process was carried out using the Renishaw Ren500S Flex printer within an argon inert gas environment to prevent oxidation and ensure optimal quality. The machine specification of the used SLM printer is listed in Table 1.

The printing parameters provide by OEM were used for printing are listed in Table 2. CAD models of the stripe shape were created and exported as .STL files using Autodesk Inventor Professional 2024 software. CAD model of stripe with dimensions are shown in Figure 3.

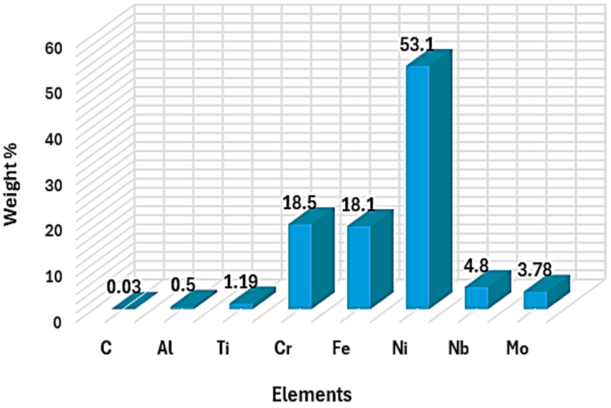


Fig. 2. Inconel 718 powder material composition.

Tab 1. Renishaw 500S Flex machine specifications.

Build Volume	250 × 250 x 350 mm^3
Laser Power	500 W
Laser Focus Diameter	80 µm
Scanning speed	7000 mm/s
Materials	In718, Stainless Steel 316L, Ti6Al4V, AlSi10Mg, In625

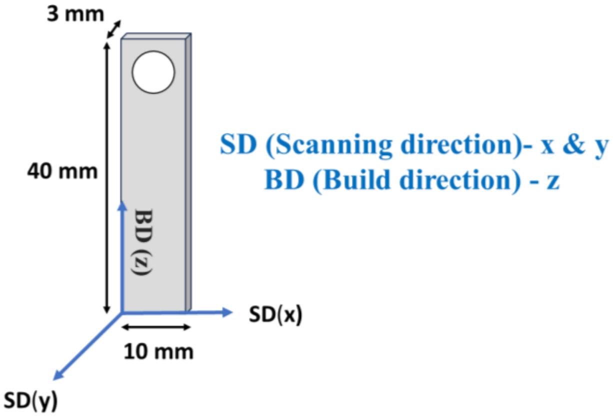


Fig. 3. Stripe CAD model with dimensions.

The exported design was imported into QuantAM to generate the 3D data for additive manufacturing. Process parameter configurations were sourced from the Material Editor, and then transferred to QuantAM for build preparation, ultimately being incorporated into a build file as part of the setup phase. Printing parameters used for the study are shown in table 2.

Tab 2. Printing parameters of SLM printer

Layer thickness	0.06 mm
Hatch distance	0.09 mm
Exposure time	77 µs
Scanning strategy	Meander
Power	200 W
Scanning speed	650 mm/s
VED	56.98 (J/mm^3)

2.1 Vibration tumbling process

The vibration-tumbling process is used to achieve a smoother and shinier surface**.** A vibration tumbler Avalon WR60 was used. The machine's speed set was 1950 rpm for the process. The tumbling working cycle of 120 min with the porcelain media and compound V6 was used in that process. That compound is used for deburring, polishing, and grinding and dosage of the compound was set to 20 ml per liter of water. Media of the vibratory tumbling process porcelain and the shape of the porcelain was cylindrical pins used for smoothing and polishing, sizes of pins are- 2×5, 2×8, 3×10 and 6×15. Porcelain plastic bonded grinding chips with a medium density are used mainly for smoothing and polishing precious metals with the addition of powder and compound. Designed for mass finishing of workpieces, suitable for deburring, grinding, radiusing, degreasing, and cleaning, processing with ceramic, plastic, and porcelain chips as well as stainless steel shot.

Suitable also for long workpieces, quick deburring through high amplitude and low frequency of vibration, possibility to divide the working bowl into 3 chambers, process consistency, homogenous result on the surface, easy and convenient emptying of the working bowl through the unloading plug, reliability- polyurethane lining of the working bowl is extremely wear resistant. Manual separating tank with trolley for abrasives, control panel with timer and frequency inverter, working table with trolley for abrasives, stainless steel stand control panel, dosing pump, and noise protection lid. During the wet grinding process, the used compounds absorb the occurring remains from the chips as well as from the material that is in the process. The purified liquid is immediately removed from the machine. The supporting compounds are selected depending on the processed material and the type of carried operation. The ingredients in the compound need to fulfill a runner of tasks in the process. They influence emulsifying sedimentation and foaming and also decrease the processed elements against corrosion or create a sliding layer on the surface of the material. All the moistening substances that are present supporting chemical solutions reduce the surface tension which makes the finishing much easier and more effective. Process parameters are shown in table 3.

Tab. 3. Process parameters of vibrational tumbling machine.

Time	Media	Compound	Speed
120 min	Porcelain	Water + V27	1950 rpm

2.2 Electrolytic polishing

An electrolytic polisher (OTECH EPAG-Smart T) was employed for the electrolytic polishing process. Following vibrational tumbling treatment, electrolytic polishing was performed to achieve superior surface finishing and smoothness. This technique involves selectively removing the outer layer of material in an appropriate electrolytic solution, significantly reducing surface roughness. The result of electropolishing is a sleek, polished metallic surface that preserves the material's underlying structure, providing improved corrosion resistance and a lasting shine. The sample underwent electrolytic polishing for 120-minute session. The process was carried out with a voltage supply of 25V and a rotational speed of 40 rpm, using electrolyte MFB (1.0). Distilled water was used to ensure a high-quality wet-finishing process. The parameters for electrolytic polishing are detailed in the table 4.

Tab. 4. Process parameters of electrolytic polishing.

Time	Speed	Voltage	Current	Electrolyte
120 min	40/min	25V	1.94 A	MFB 1.0

In Table 5, the surface treatment processes, and their durations are described in detail. These procedures were applied to improve the surface quality of the SLM-printed specimens. Sample 1 underwent electrolytic polishing for 120 mins, sample 2 was subjected to vibratory tumbling with porcelain media for 120 mins and Samples 3 underwent vibratory tumbling for 120 minutes followed by electrolytic polishing of 120 minutes. Figure 4 provides a summary of the fabrication process, post-treatment techniques, and surface characterization methods.

Tab. 5. Processing methods and durations applied to Inconel 718 samples in their as-built state.

Sample no.	Electrolytic polishing	Vibrational tumbling	Total Time
	120 min	**120 min**	**min**
1	*		120
2		*	120
3	*	*	240

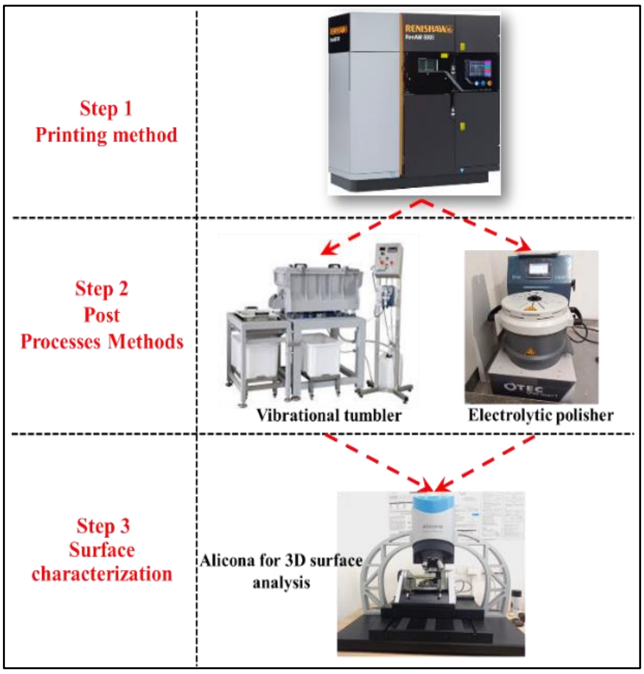


Fig. 4. The diagram depicts the fabrication process, post treatments, and methods for surface analysis.

2.3 Characterization techniques

To assess the influence of post-processing processes on surface characteristics, microstructure, and 3D surface roughness, the Alicona Infinite Focus G5 optical microscope was utilized. The 3D surfaces scanned by the Alicona microscope was analyzed using MountainsLab software. Surface texture roughness was evaluated by measuring areal surface roughness parameters, specifically the arithmetic mean height (Sa), the maximum height (Sz), the maximum peak height (Sp), and the maximum valley height (Sv). We selected Sa, Sz, Sp, and Sv instead of Ra because they provide a more comprehensive analysis of surface topography. Unlike Ra, which measures average roughness in 2D, Sa captures the mean height in 3D. Sz indicates the full height range from peak to valley, and Sp and Sv focus on the highest peaks and lowest valleys. This detailed information is essential for a more accurate understanding and control of surface characteristics.

2.4 Contact angle measurements

Wettability of the samples was measured using the sessile drop method with deionized (DI) water. Tests were performed at 25°C and varying humidity from 50% to 5%. Samples were pre-cleaned in isopropyl alcohol and deionized water for 15 minutes each. Drops (1-1.5 mm in diameter) were applied using a needle-syringe system, and the contact angle (CA) was measured by capturing images with a high-speed camera and analyzing them with ImageJ software.

3. RESULT AND DISCUSSIONS

3.1 Surface roughness

The surface treatment processes were applied to all SLM-printed samples. The study involved two types of post-processing on the as-built samples Sample 1 was subjected to electrolytic polishing for 120 minutes. Sample 2 underwent vibrational tumbling for 120 minutes. Sample 3 received a combination of vibrational tumbling and electrolytic polishing, with the tumbling process using porcelain media, followed by 120 minutes session of electrolytic polishing. The total processing time was 240 minutes.

Optical profilometry was employed to examine the surface roughness of additively manufactured samples under different conditions. The study assessed areal surface roughness parameters to gain a better understanding of the surface characteristics. To ensure consistency in the measurement conditions, 3x3 mm sections were scanned at five distinct sample sites. This approach provided a thorough representation of surface roughness with significantly more data points compared to traditional methods. The mean surface roughness values after optimization through vibrational tumbling and electrolytic polishing are detailed in Table 6. Vibrational tumbling reduces surface roughness by up to 32%, whereas electrolytic polishing achieves a 12% reduction. In total, the surface roughness decreases by nearly 40% from the initial value. Initially, the roughness values of all samples were roughly equivalent. For further analysis, the highest values, Sa (5.68 µm) and Sz (53.36 µm), in the as-built condition are used as benchmarks for comparison with all post-processed values.

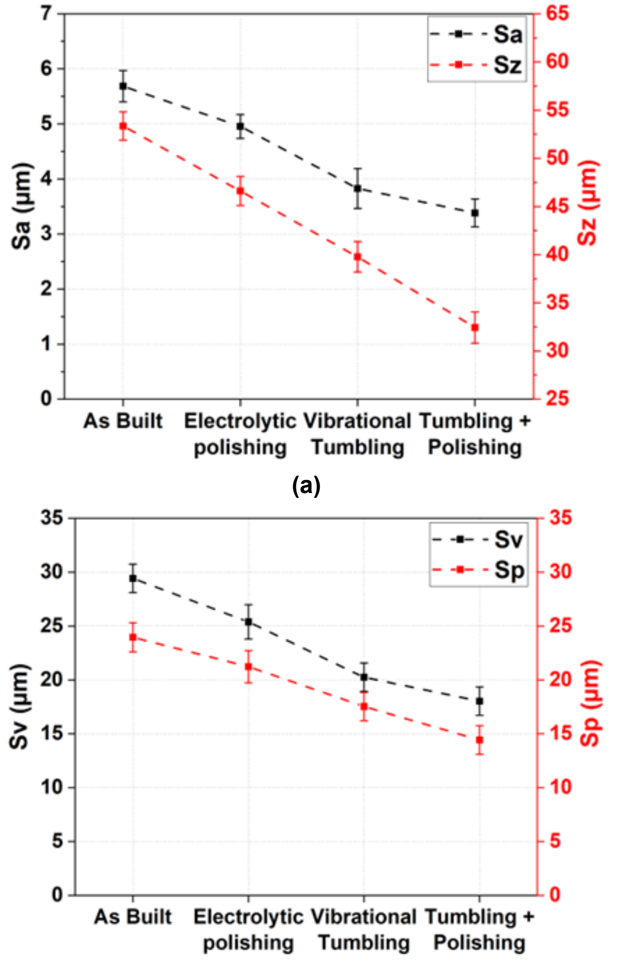
Tab. 6. The mean surface roughness (Sa, Sz, Sv and Sp) values following post-optimization via Vibrational tumbling, and Electrolytic polishing.

	***Sa* µm**	***Sz* µm**	***Sv* µm**	***Sp* µm**
As Built	*5.68±0.283*	*53.36±1.473*	*29.418 ±1.317*	*23.942 ±1.357*
Electrolytic polishing	*4.95±0.217*	*46.61±1.509*	*25.384 ±1.580*	*21.226 ±1.498*
Vibrational tumbling	*3.83±0.361*	*39.77±1.586*	*20.244 ±1.312*	*17.526 ±1.325*
Vibrtaional tumbling+ Electrolytic polishing	*3.38±0.253*	*32.444 ±1.615*	*18.026 ±1.317*	*14.418 ±1.325*

For sample no 1, 120-minute electrolytic polishing reduced the surface roughness by 12% from the as built condition, with Sa reduced from (5.68 to 4.95 µm), Sz decreased from (53.36 to 46.61 µm), Sv (29.41 to 25.38 µm), Sp (23.94 to 21.22 µm). This post process method improved surface smoothness and produce a high-quality finish. However, electrolytic polishing generally removes less material than tumbling process. This is due to the electrochemical process, which selectively dissolves only the surface layer, smoothing it rather than making substantial changes to the overall material volume. As a result, while electrolytic polishing is effective for enhancing surface quality, its impact on reducing roughness is limited because of its lower material removal rate. In this method effectively removes the tallest peaks while preserving the deeper valleys on the surface (Figure 5). Polishing is the process of refining a workpiece's surface to achieve a smooth, glass-like finish. The electrolytic polishing is also used to enhance the surface quality of metallic materials produced through additive manufacturing, with a particular emphasis on improving fatigue resistance.

For Sample no 2, 120 minutes of vibrational tumbling led to a 32% reduction in surface roughness from as built state, with Sa decreased from (5.68 to 3.83 µm), Sz decreased from (53.36 to 39.77 µm), Sv (29.41 to 20.24 µm), Sp (23.94 to 17.52 µm). This method showed its capability to uniformly smooth and deburr surfaces. However, vibrational tumbling generally results in less material removal compared to more aggressive methods due to its use of relatively gentle abrasive media and constant, low-intensity agitation. As a result, while it effectively smooths surfaces, its impact on reducing surface roughness is limited by its lower material removal rate. Machine produces vibrations that make the media and parts continuously tumble and interact. This agitation results in a rubbing or grinding effect on the parts' surfaces. Vibratory tumbling with porcelain media usually leads to a slower material removal rate compared to more aggressive media such as ceramic or silicon carbide. Porcelain media is primarily employed for light deburring, polishing, and surface smoothing rather than heavy material removal**.** These values are inadequate for enhancing the surface texture of the samples**.**

For Sample no 3, vibrational tumbling for 120 minutes reduced surface roughness by 32%. This was followed by 120 minutes of electrolytic polishing, which further reduced surface roughness by 11.60%. Overall, the surface roughness decreased by 40% from the initial value, with Sa decreasing from (5.68 µm to 3.38 µm), Sz (53.36 to 32.44 µm), Sv (29.41 to 18.026 µm), Sp (23.94 to 14.41 µm). The combination of vibrational tumbling and electrolytic polishing resulted in a nearly 40% reduction in surface roughness by targeting irregularities at different scales. Vibrational tumbling removes larger surface features like asperities and burrs, mainly reducing roughness on a macro scale. Electrolytic polishing then fine-tunes the surface by selectively removing microscopic peaks, producing a smoother finish at the micro level. Together, these methods are more effective than when used separately, as vibrational tumbling prepares the surface for electrolytic polishing, leading to a more consistent and significant reduction in surface roughness.



(a)

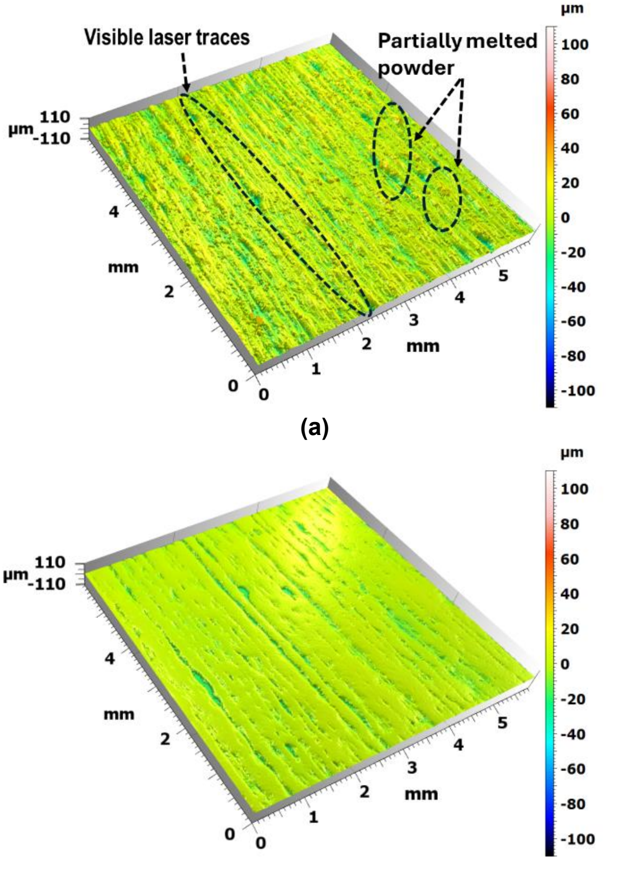
(b)

Fig. 5. Assessment of areal surface roughness parameters: 5(a) Sa and Sz, 5(b) Sv and Sp.

3.2 Surface topology

Fig. 6 displays the 3D surface topology of as-built SLM samples, which initially have rough textures, partially melted particles, and visible laser traces. Post-processing techniques, including vibrational tumbling, and electropolishing, greatly improve surface quality. Vibratory tumbling significantly decreases surface roughness, it may leave behind some residual valleys and imperfections. Electrolytic polishing enhances the surface to a highly polished state with minimal material loss. When combined with other methods, it significantly reduces roughness and waviness but may require additional polishing for a uniform finish. These treatments result in about a 40% reduction in surface profile elevation from the as-built state, with vibratory tumbling and electropolishing achieving the smoothest surface finishes.

Vibrational tumbling uses abrasive media in a vibrating container to remove larger surface defects, resulting in a matte finish and reduced macro-scale roughness. Electrolytic polishing employs an electrochemical process to selectively dissolve surface peaks, creating a smooth, mirror-like surface and minimizing micro-scale roughness. While vibrational tumbling is suited for deburring and overall smoothing, electrolytic polishing achieves high-precision, refined surface finishes.



(a)

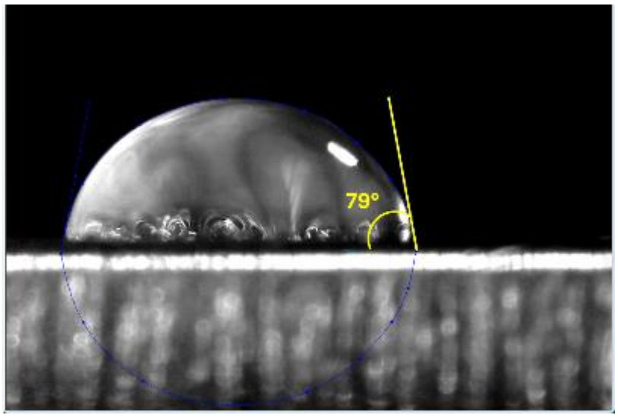
(b)

Fig. 6. Comparative Surface Morphology of Additively Manufactured Samples Before and After Vibratory Tumbling and Electropolishing.

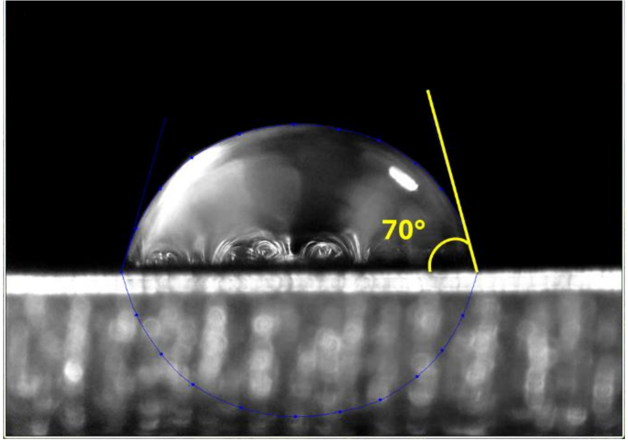
3.3 Wettability

The wettability of the specimens was assessed using the sessile drop technique, focusing on measuring contact angles. The analysis examined how contact angles for deionized (DI) water droplets varied on SLM surfaces following different post-processing treatments. These treatments resulted in decreased contact angles. During the evaluation, droplets were deposited on the surfaces, which served as a barrier for the solid-liquid interface. The existing surface roughness facilitated the spreading of the droplets, suggesting that the SLM surfaces exhibit hydrophilic properties and a strong affinity for water (Dwivedi et al., 2022).

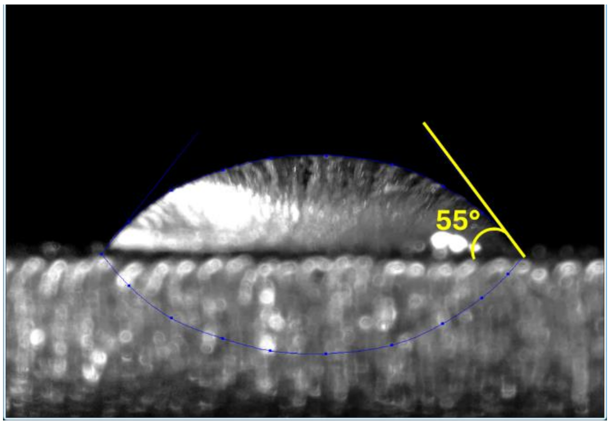
Fig. 7 shows, electrolytic polishing although it produces a very smooth and clean surface, resulted in a contact angle of 70°, potentially due to residual contaminants or a specific surface chemistry that is less hydrophilic. Vibrational tumbling is more effective at smoothing the surface, reducing the contact angle to 55°.When combined, these methods achieve the lowest contact angle 46°, indicating a synergistic effect. This outcome may be due to the optimal combination of surface roughness and cleanliness, creating ideal conditions for liquid dispersion. The smaller contact angle suggests that all three methods enhance the hydrophilicity of the AM surfaces, demonstrating that SLM surfaces show improved wettability after undergoing these post-processing techniques (Dwivedi, Dixit, Das, & Srivastava, 2023). Understanding the wettability parameters in form of contact angle is crucial as they influence adhesion, corrosion resistance, and overall surface performance of the printed components.



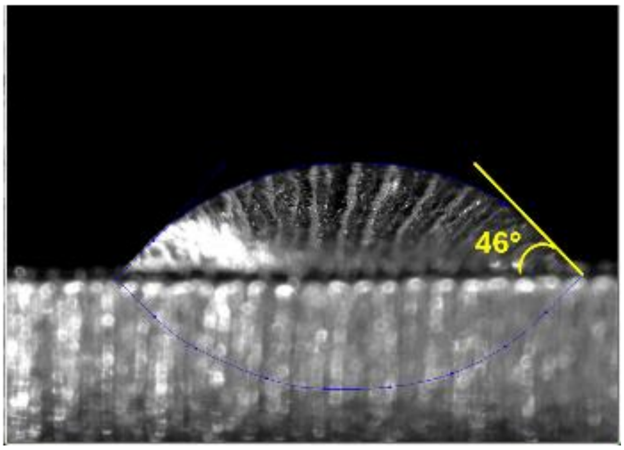
(a) As built



(b) Electrolytic polishing



(c) Vibrational tumbling



(d) Vibrational tumbling+ Electrolytic polishing

Fig. 7. Contact angle measurements after post processing (a) As built, (b) Electrolytic polishing, (c) Vibratory tumbling and (d) Vibrational tumbling+ Electrolytic polishing

4. CONCLUSION

The study investigates the impact of vibrational tumbling and electrolytic polishing on the surface roughness of SLM-printed Inconel 718. The key findings include:

1. Electrolytic polishing reduces surface roughness by 12% from as built surface. However, this method was less effective than tumbling.
3. Vibrational tumbling with porcelain media achieved the greatest reduction, lowering the roughness values by 32%.
4. Using both methods together reduced surface roughness by nearly 40%, improving both mechanical and aesthetic properties.
5. Surface topology images showed reduced defects like micropores and cracks, enhancing part integrity in the post processed samples.
6. Surface wettability study showed improvement in hydrophilic property of the surface, with contact angles decreasing from 79° to 46° after post processing.

The research highlights the critical role of post-processing in optimizing surface quality for high-performance alloys like Inconel 718.

The notable reduction in surface roughness from vibrational tumbling and electrolytic polishing is vital for sectors such as aerospace, automotive, and medical device manufacturing, where superior surface quality is essential for better performance, increased durability, and enhanced resistance to wear and corrosion.

5. ACKNOWLEDGMENTS

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