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Abrasive Flow Machining of Additively Manufactured Inconel 718 Conformal Cooling Channels: Effects on Surface Integrity and Tribological Performance

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ABSTRACT

Poor surface quality of conformal cooling systems manufactured using additive manufacturing processes can adversely affect flow characteristics, particularly laminar flow. Although numerous post-processing techniques are available, only a limited number are suitable for finishing internal channels, one of which is Abrasive Flow Machining (AFM). In this study, the effect of AFM process parameters, including media concentration ratio, number of cycles, and abrasive grain size on the surface quality of Inconel 718 holes manufactured by the Powder Bed Fusion Laser Beam (PBF_LB) process were investigated in terms of surface integrity characteristics, including surface topography, surface roughness, microhardness, and tribological performance. Experimental results showed that unmelted particles were effectively removed from the surface, resulting in 98% reduction in surface roughness. However, the lowest coefficient of friction, representing a reduction of 0.58 compared with the as-built condition, was obtained at a media concentration of 60% and 80 AFM cycles. In addition, the roughness of heat-treated samples improved by 15% after AFM compared with that of the non-heat-treated samples.

Keywords: Abrasive flow machining, Additive Manufacturing, Post-process, Inconel 718, Conformal cooling

1 Introduction

Inconel 718 is a nickel-based superalloy with excellent high-temperature strength and corrosion resistance. Its stable microstructure and high fatigue resistance, even at elevated service

temperatures, make Inconel 718 an ideal material for turbine components, aerospace applications, and heat exchangers.

Additive manufacturing (AM) enables the production of components with complex geometries that are difficult or impossible to manufacture using traditional manufacturing methods. By combining AM with topology optimization, lighter, more material-efficient components with lattice structures can be fabricated. AM also enables the fabrication of efficient conformal cooling channels, especially for casting molds and components operating under high-temperature service conditions.

One of the most significant disadvantages of additive manufacturing (AM) is the poor surface quality of manufactured components. AM components manufactured by powder bed fusion (PBF) techniques (laser- or electron-beam-based) often exhibit poor surface quality due to the presence of unmelted metal powder particles [1]. In aerospace applications, high-performance alloys such as Inconel 718 require excellent surface quality, which plays a critical role in achieving optimum high-temperature performance. This can be improved through appropriate post-processing techniques.

Numerous studies have demonstrated that various post-processing techniques can be applied to AM components. These techniques can be classified into categories such as mechanical, chemical, laser-based, hybrid, and coating processes [2,3]. The complexity of the surface being treated is often a key factor in determining the most appropriate post-processing technique. For example, mechanical methods may be preferred for flat surfaces, whereas chemical methods may be more suitable for delicate, thin-walled lattice structures.

Furthermore, only a limited number of methods are available to improve the surface quality of conformal cooling channels. These channels often feature angled, concave, convex, and complex geometries. Therefore, methods that can process the internal surfaces throughout the entire channel length are required. Chemical-based electropolishing can be applied for this purpose. However, these methods are operator-dependent and immersion-based, resulting in variable process outcomes. Moreover, erosion and cracking may occur because of excessive immersion time, particularly in regions where the component has thin-walled lattice structures surrounding the internal channels [4].

Abrasive flow machining (AFM) is an abrasive finishing process that uses a viscoelastic polymer medium containing abrasive particles, which is extruded through internal channels or

across complex surfaces under pressure [5]. Therefore, it selectively processes only the target surface, making it an ideal post-processing method for conformal cooling channels.

Previous studies have clearly demonstrated the influence of AFM process parameters on surface quality. Basha et al. [6] investigated the effects of different AFM parameters on the surface topography of PBF-LB-processed 316L stainless steel. A coarser abrasive grit size resulted in lower surface roughness and a higher material removal rate. Seyedi et al. [7] investigated the effect of abrasive media type and reported that media containing Al_2O_3 abrasive particles produced higher surface roughness compared with media containing SiC and B_2O_3 particles. Bremerstein et al. [8] showed that a higher piston speed increases the material removal rate and also reduces surface roughness. Dixit et al. [9] reported that increasing the extrusion pressure reduced surface roughness. Hashmi et al. [10] investigated the effect of abrasive media viscosity and reported that higher media viscosity resulted in lower surface roughness because higher viscosity increases the shear force generated during the finishing process. Duval-Chaneac et al. [11] investigated the effect of abrasive media concentration and reported lower surface roughness at higher media concentrations. Some studies have shown that surface roughness decreases with increasing number of AFM cycles. However, a very high number of cycles does not necessarily continue to improve the surface quality [12–14].

There are studies reporting the application of the AFM process to AM samples manufactured from different materials, such as 316L [15], Ti6Al4V [16], 42CrMo4 [17], AlSi10Mg [18], maraging steel [19], and even PLA [20] and ABS [21]. However, most of these studies have focused on flat surfaces. In particular, the number of studies investigating the AFM process on internal holes is very limited. In one of these studies, Han et al. [22] investigated the effect of AFM on the surface quality of straight and curved internal channels produced by additive manufacturing from maraging steel. They reported that the surface quality improved by up to 81%. Therefore, a more detailed investigation into improving the surface quality of additively manufactured internal channels using AFM is needed. This is because the surface quality of internal flow channels directly affects the laminar-to-turbulent flow transition of the fluid, and the potential of the AFM process to improve this performance has yet to be fully explored.

In this study, the effect of AFM process parameters on additively manufactured Inconel 718 perforated coupons was systematically investigated in terms of surface integrity characteristics, including surface roughness, surface topography, microhardness, and wear behavior. Furthermore, the mechanical properties of the Inconel 718 coupons were modified by heat treatment, and the material's response to the AFM process was compared between the heat-

treated and as-built conditions. Statistical analysis was performed to determine the significance of the AFM process parameters with respect to surface quality.

2 Materials and Methods

2.1 Workpiece Material

The workpieces used in this study are Inconel 718 alloy coupons manufactured by the Laser Powder Bed Fusion–Laser Beam (PBF-LB) process, as shown in Fig. 1. The coupons measure $15 \times 15 \times 20$ mm and contain a through-hole with a diameter of 6 mm. These coupons were produced using an Ermaksan Enavision 250 machine. The Inconel 718 alloy powder was supplied by AP&C GE Additive. The metal powder, supplied in accordance with the UNS N06625 and UNS N07718 standards specifying the chemical composition of nickel-based alloy powders, had a particle size distribution (PSD) in the preferred range of 15–45 μm (typical particle size ranges: 0–20 μm , 15–45 μm , 15–63 μm , 45–106 μm , and 45–150 μm).

The coupons examined in this study are hereafter referred to as IN718, IN718-U, and IN718-U-HT, representing the straight-hole as-built, application-hole as-built, and heat-treated application-hole samples, respectively. For the IN718-U-HT coupons, heat treatment was performed as a post-processing operation using a vertical furnace under atmospheric conditions. The as-built specimens were heat-treated at 1100 °C for 2 h, followed by air cooling, according to the industrial standard heat-treatment procedure for cast Inconel 718 [23].

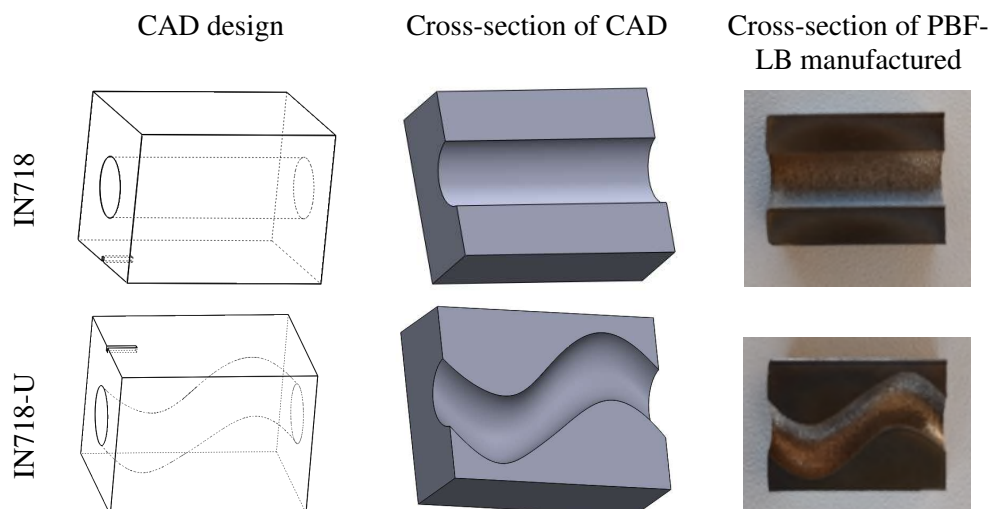


Fig. 1. Designed and PBF-LB-manufactured Inconel 718 coupons.

2.2 Abrasive Flow Machining

In this study, a two-way AFM machine available at Gaziantep University was used. The AFM machine consists of a main body, a workpiece holder, a control system, and a hydraulic system. The hydraulic system provides the pressure and flow required for the AFM process. The control unit adjusts the AFM process parameters defined by the experimental design. Detailed information about the AFM machine can be found in a previous study [24].

In the AFM process, the abrasive medium is prepared by adding abrasive particles to a polymer carrier at a specified concentration. Silicon carbide (SiC) was used as the abrasive. Hydraulic oil was added to ensure that the polymer adhered to the workpiece and to facilitate the flow of the abrasive medium. Under high pressure, the abrasive medium hardens and acts like a grinding wheel. This characteristic allows it to conform to the geometry of the surface being treated, thereby producing a polishing effect. The abrasive concentration was defined as the weight of the abrasive particles $\times 100 / (\text{total weight of the abrasive medium})$. Abrasive particles with F180 and F240 mesh sizes were used to achieve the desired concentration. Abrasive media was prepared with abrasive-to-polymer ratios of 40%, 50%, and 60%.

Experiments were conducted on IN718 coupons at 5, 10, 20, 40, and 80 processing cycles and on IN718-U coupons at 1, 5, 10, 20, and 40 processing cycles. One processing cycle was completed by moving the upper and lower pistons from the lowest position to the highest position and back to the lowest position. The AFM experimental design is presented in Table 1. The workpiece holder shown in Fig. 2 was designed to hold the coupons during the AFM process. A new coupon was used for each experiment, and a total of 35 AFM experiments were performed.

Table 1. AFM experimental design with SiC abrasive.

Design code	Abrasive media grit size (FEPA)	Media concentration	Cycle
IN718	F180 (53-90 μm)	%40	5, 10, 20, 40, 80
		%60	5, 10, 20, 40, 80
IN718	F240 (28-70 μm)	%40	5, 10, 20, 40, 80
		%50	5, 10, 20, 40, 80
		%60	5, 10, 20, 40, 80
IN718-U	F240 (28-70 μm)	%60	1, 5, 10, 20, 40
IN718-U-HT	F240 (28-70 μm)	%60	1, 5, 10, 20, 40

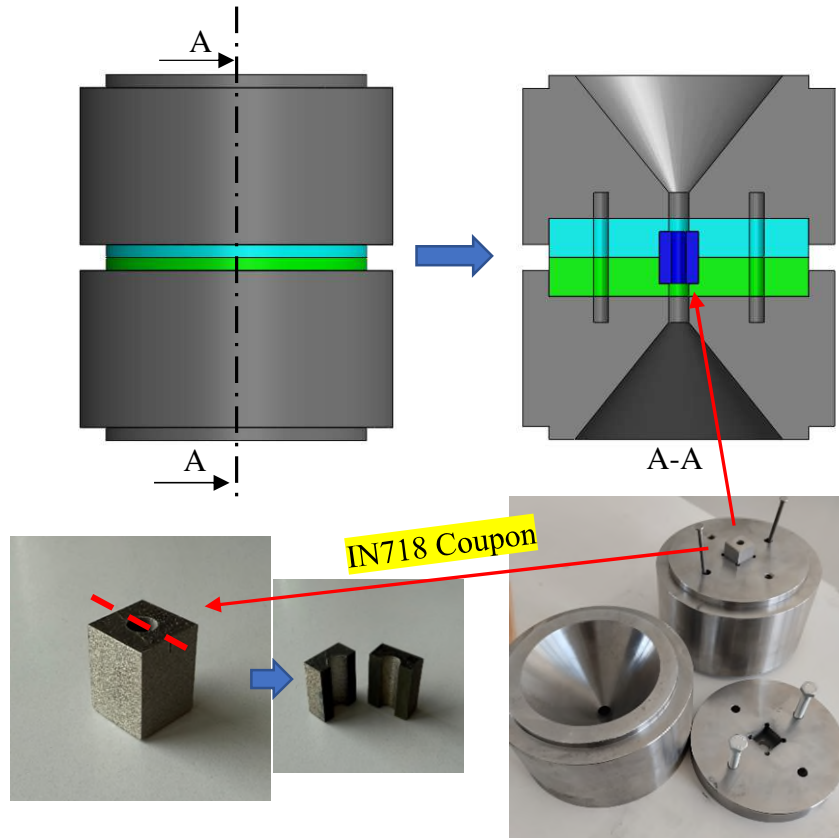


Fig. 2. Designed and fabricated workpiece holder for the AFM process.

2.3 Measurements

Machined specimens were cold-mounted in cross-section and polished using conventional metallographic techniques. The polished specimens were etched using a solution of 16.7 vol.% HNO_3 + 33.3 vol.% glycerol + 50 vol.% HCl . The microstructure and AFM-induced surface layers were examined using a Keyence VHX-6000 digital optical microscope. SEM images were acquired using a Philips XL30 scanning electron microscope. Microhardness measurements were performed using a Future-Tech FM-310e microhardness tester in accordance with ASTM E384. The microhardness of each specimen was determined from the average of five measurements.

A reciprocating tribometer was used to conduct dry sliding wear tests in accordance with ASTM G133. The wear tests were performed for 40 min under a 5 N normal load with a 6 mm stroke length. All the tests were carried out at room temperature under ambient air. A 3 mm diameter tungsten carbide ball (94 wt.% WC–6 wt.% Co) was used as the counterface in the reciprocating wear tests.

3 Results and Discussions

3.1 Surface Roughness and Topography

3.1.2 Effect of AFM process parameters

The as-built surface roughness of the IN718 coupon is presented in Figure 4. The density of unmelted particles on the scanning (x–y) plane is lower than that on the build (z) plane. The surface roughness of the scanning plane was measured as 3 μm . The surface roughness of the internal channel and the build plane was $16 \pm 2 \mu\text{m}$ and $14 \pm 2 \mu\text{m}$, respectively. Measurements performed on the build plane show the variability in the diameters of the unmelted particles. These particle diameters range from 15 to 45 μm , which is consistent with the powder particle size distribution. Consequently, different roughness values were obtained from different measurement locations. Therefore, the presence of error bars reflects this inherent variability.

However, the difference between the channel and build-plane roughness cannot be explained solely by the particle size distribution but is also attributed to the geometric characteristics of the component. The build (z) plane is flat, whereas the internal channel has a circular cross-section. The density of unmelted particles adhering to the surface during the fabrication of the internal channel differs from that on the flat build surface. The higher density of unmelted particles within the channel resulted in higher surface roughness compared with the build plane.

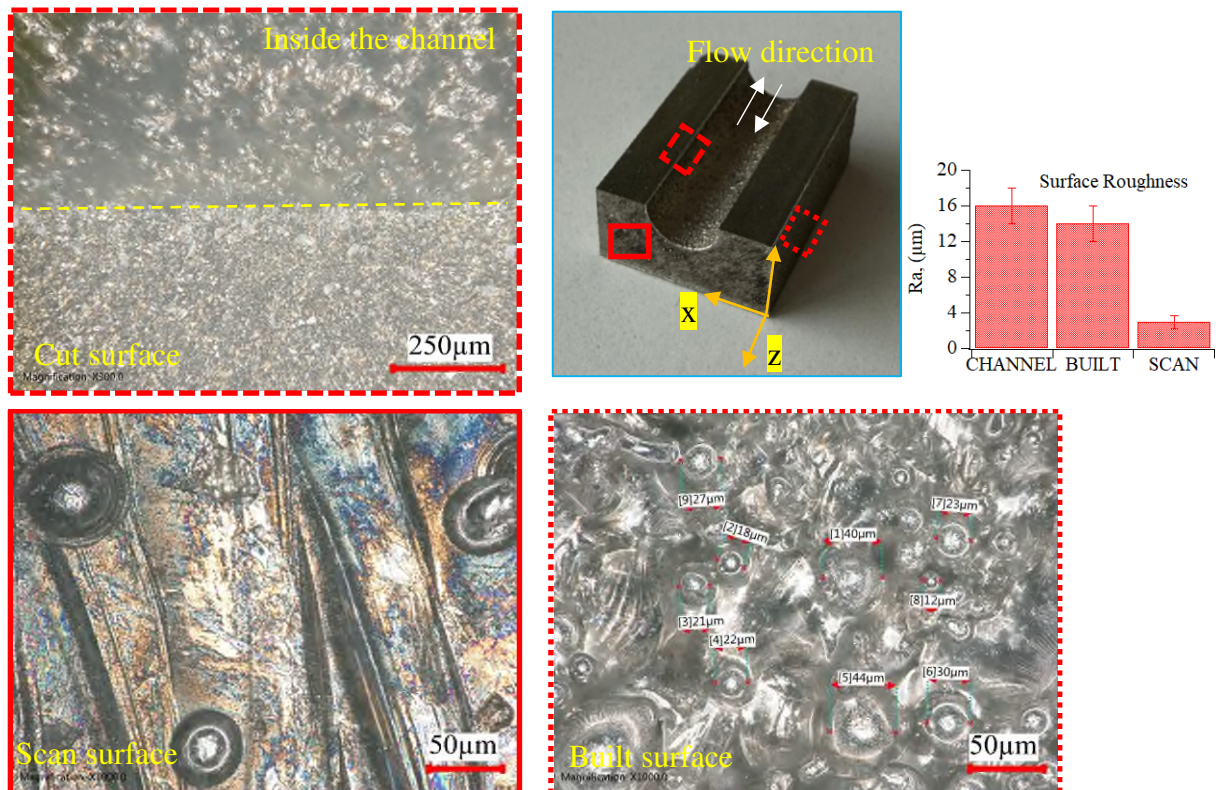


Fig. 4. As-built IN718 surface topography images and surface roughness values.

Three-dimensional topographic images obtained inside the channels of the IN718 specimens after AFM processing using F240 SiC abrasive particles are presented in Figure 5 as a function of the number of cycles and abrasive media concentration. Unlike the as-built surface, the topographic images showed no adhered unmelted metal particles. Therefore, the contribution of the AFM process to improving the surface quality of additively manufactured components was clearly confirmed. The unmelted metal particles were completely removed starting from the fifth cycle for abrasive media concentrations of 40%, 50%, and 60%.

However, as the number of cycles increased, surface waviness became more pronounced at 40% and 50% media concentrations, whereas no such waviness was observed at 60%. These surface undulations appeared from cycle 10 at the 40% concentration and from cycle 40 at the 50% concentration, aligned with the flow direction of the abrasive medium. Their morphology resembled a crumpled-paper-like surface.

At a 60% abrasive media concentration, the surface topography continuously improved as the number of cycles increased. The resulting surface topography was similar to that of conventionally cold-drawn materials, with no evidence of surface waviness. However, abrasive impact marks were still observed during the first 20 processing cycles.

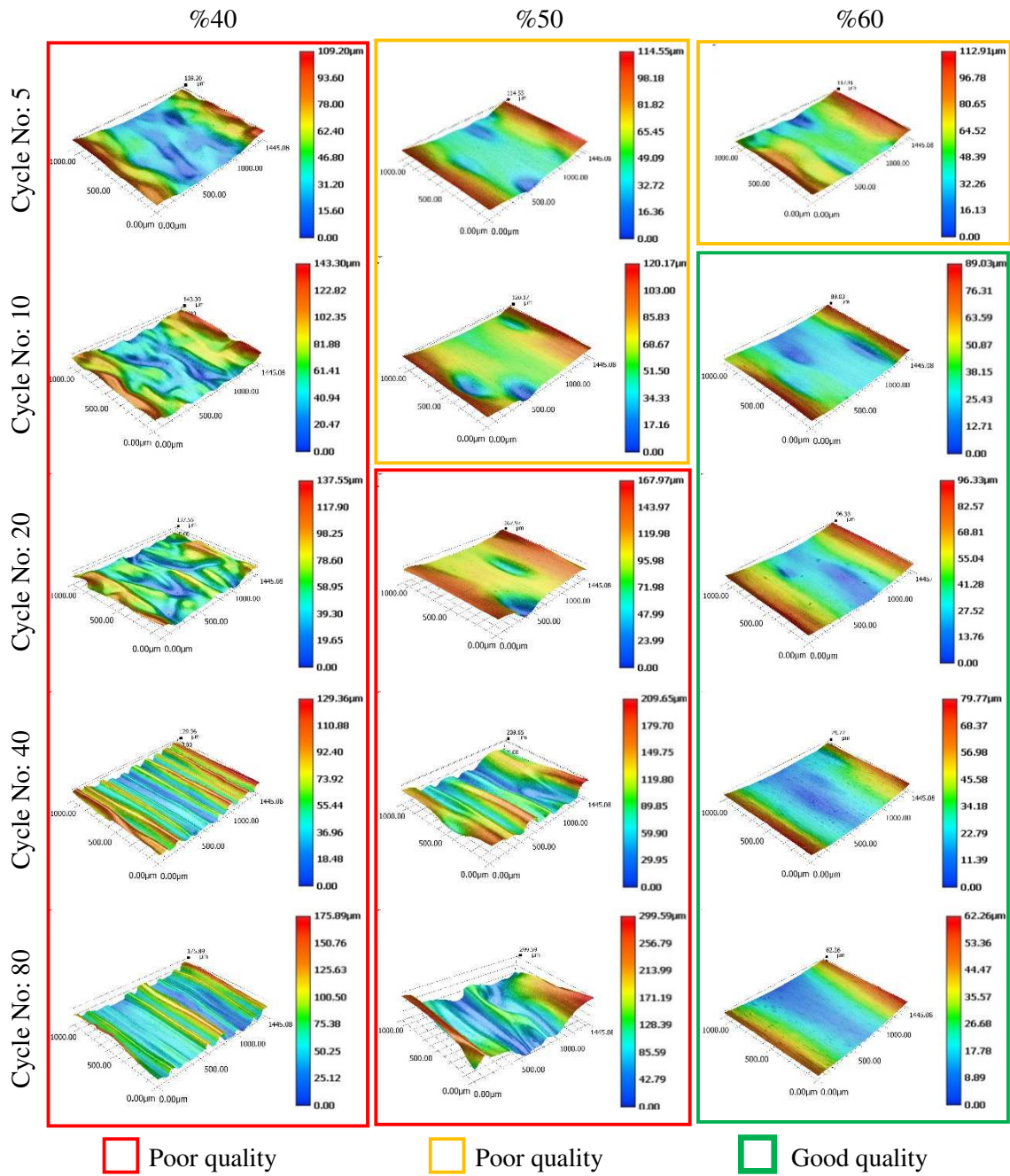


Fig. 5. Three-dimensional surface topography of the internal channels after AFM processing (Abrasive grain size: F240).

Figure 6 shows three-dimensional surface topography images of the internal channel obtained after AFM experiments conducted with F180 SiC abrasive at 40% and 60% abrasive media concentrations. The presence of unmelted metal powder adhering to the surface was no longer observed after the fifth processing cycle. At a 40% abrasive media concentration, surface waviness became more pronounced as the number of cycles increased. In contrast, at a 60% abrasive media concentration, a smooth and homogeneous surface topography was obtained. Overall, F180 and F240 abrasive grain sizes produced similar trends in surface topography as

a function of the number of cycles. Among the AFM process parameters investigated, abrasive media concentration had the greatest influence on surface topography, with a 60% abrasive media concentration consistently producing the desired topography for both abrasive grain sizes.

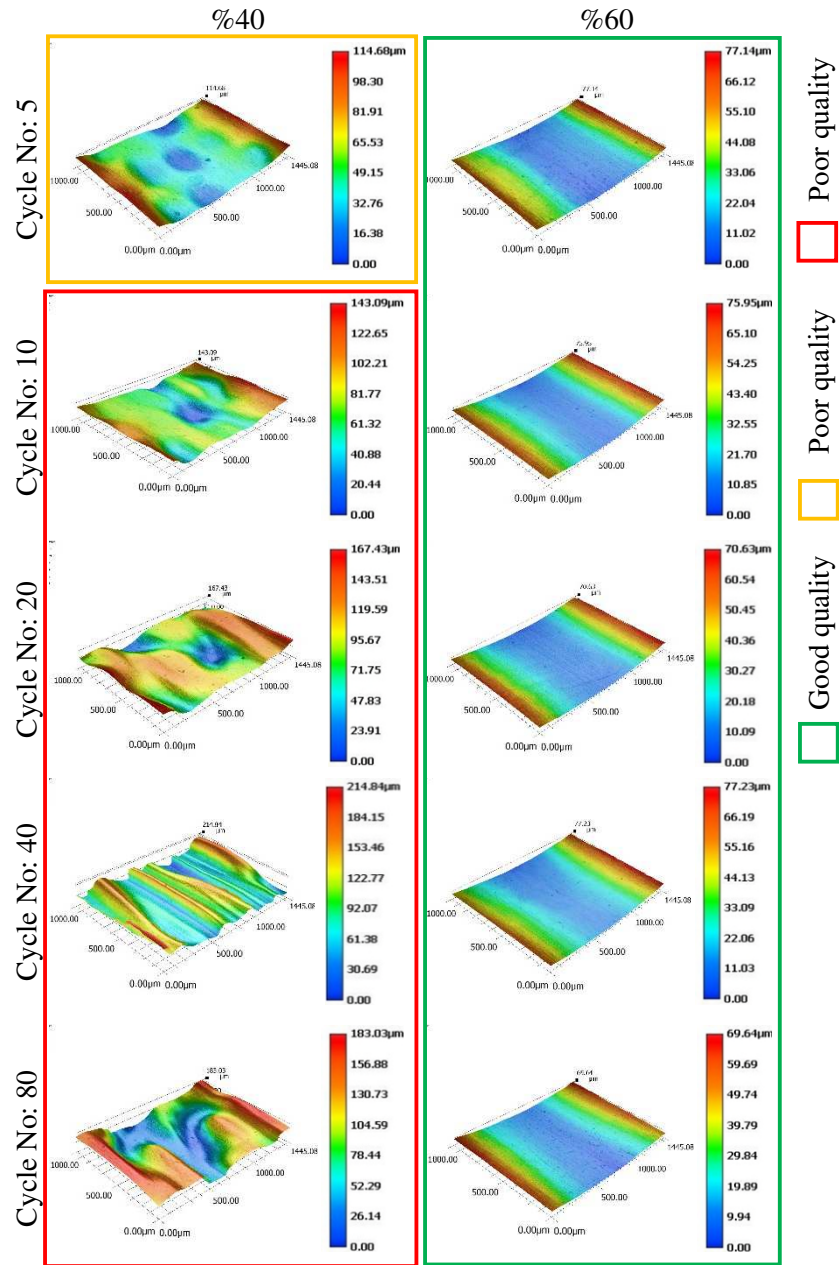


Fig. 6. Three-dimensional surface topography of the internal channels after AFM processing (Abrasive grain size: F180).

After evaluating the surface topography, the roughness of the coupons was measured. The roughness measurements revealed that, despite the progressive deterioration in surface topography as the number of cycles increased, the roughness values exhibited a trend that did not fully correspond to the topographical observations. This phenomenon can be better

explained using the two-dimensional topographic images shown in Figure 7. Since the Ra parameter represents the arithmetic average roughness measured along a single line, the influence of surface undulations on measurements taken parallel to the abrasive media flow direction can be limited. In contrast, measurements performed perpendicular to the flow direction may yield higher Ra values because they intersect the surface undulations.

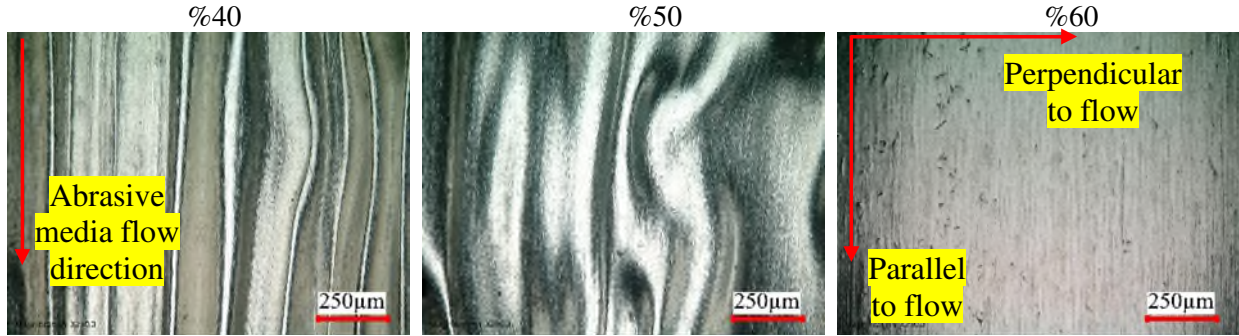


Fig. 7. Two-dimensional surface topography images and surface roughness measurement directions (F240 abrasive, 80 processing cycles).

Figure 8a shows the surface roughness values of the internal channels measured parallel to the abrasive media flow direction after the AFM experiments. A dramatic decrease in surface roughness was observed after the fifth processing cycle. At cycle 5, the lowest roughness value ($R_a = 0.43 \mu\text{m}$) was obtained using F180 abrasive with a 60% media concentration. This represents a 97% reduction compared with the as-built surface roughness. The highest roughness value ($R_a = 7 \mu\text{m}$) was obtained using F240 abrasive with a 40% media concentration. At a 60% media concentration, surface roughness continued to decrease with increasing number of processing cycles. It is clear that abrasive media concentration was the most influential process parameter affecting surface roughness, as a significant difference was observed between the 40% and 60% media concentrations. At 80 processing cycles, the roughness values obtained with F180 abrasive were $3.36 \mu\text{m}$ and $0.27 \mu\text{m}$ for the 40% and 60% media concentrations, respectively. The corresponding values for F240 abrasive were $2.8 \mu\text{m}$ and $0.30 \mu\text{m}$, respectively.

Figure 8b shows the surface roughness values measured perpendicular to the abrasive media flow direction for different abrasive grain sizes and media concentrations. At a 60% media concentration, a consistent reduction in surface roughness was observed with increasing number of processing cycles, regardless of the SiC abrasive grain size. However, at a 40% media concentration, surface roughness began to increase after 20 processing cycles for F180 abrasive and after 5 processing cycles for F240 abrasive. This behavior is attributed to the

development of surface waviness (wrinkling) despite the apparent improvement in local surface finish. The lowest roughness value measured parallel to the flow direction was 0.27 μm , whereas the minimum value measured perpendicular to the flow direction was 1.7 μm .

Therefore, the R_a parameter alone makes it difficult to draw definitive conclusions regarding the surface quality achieved by AFM. Areal roughness (S_a) is considered a more appropriate parameter because it represents the average roughness over a defined surface area rather than along a single measurement line, as in the case of R_a . The difference between the R_a and S_a roughness parameters is illustrated in Equations (1) and (2) [25].

$$R_a = \frac{1}{L} \int_0^L |y| dx \quad (1)$$

$$S_a = \frac{1}{A} \iint_A |Z(x, y)| dx dy \quad (2)$$

Figure 8c shows the effects of different abrasive media concentrations on areal surface roughness (S_a). In this study, the S_a parameter may be regarded as representing the overall average surface roughness because it accounts for roughness variations in all directions, unlike R_a , which is measured along a single profile. Accordingly, the results show a similar overall trend between R_a and S_a . At a 60% abrasive media concentration, a consistent decrease in S_a was observed as the number of processing cycles increased. In contrast, at 40% and 50% media concentrations, S_a exhibited a non-uniform trend, increasing after prolonged processing due to the development of surface waviness.

Figure 8d demonstrates the effect of abrasive grain size on surface quality at different abrasive media concentrations. Because F180 SiC abrasive particles are coarser than F240 particles, they initially produced a greater reduction in surface roughness at a 60% media concentration. However, as the number of processing cycles increased, both F180 and F240 abrasives achieved comparable surface quality. Another important finding is that, despite the difference in abrasive grain size, the overall roughness evolution followed a similar trend for both abrasives, indicating that abrasive media concentration and the number of processing cycles had a greater influence on the final surface quality than abrasive grain size.

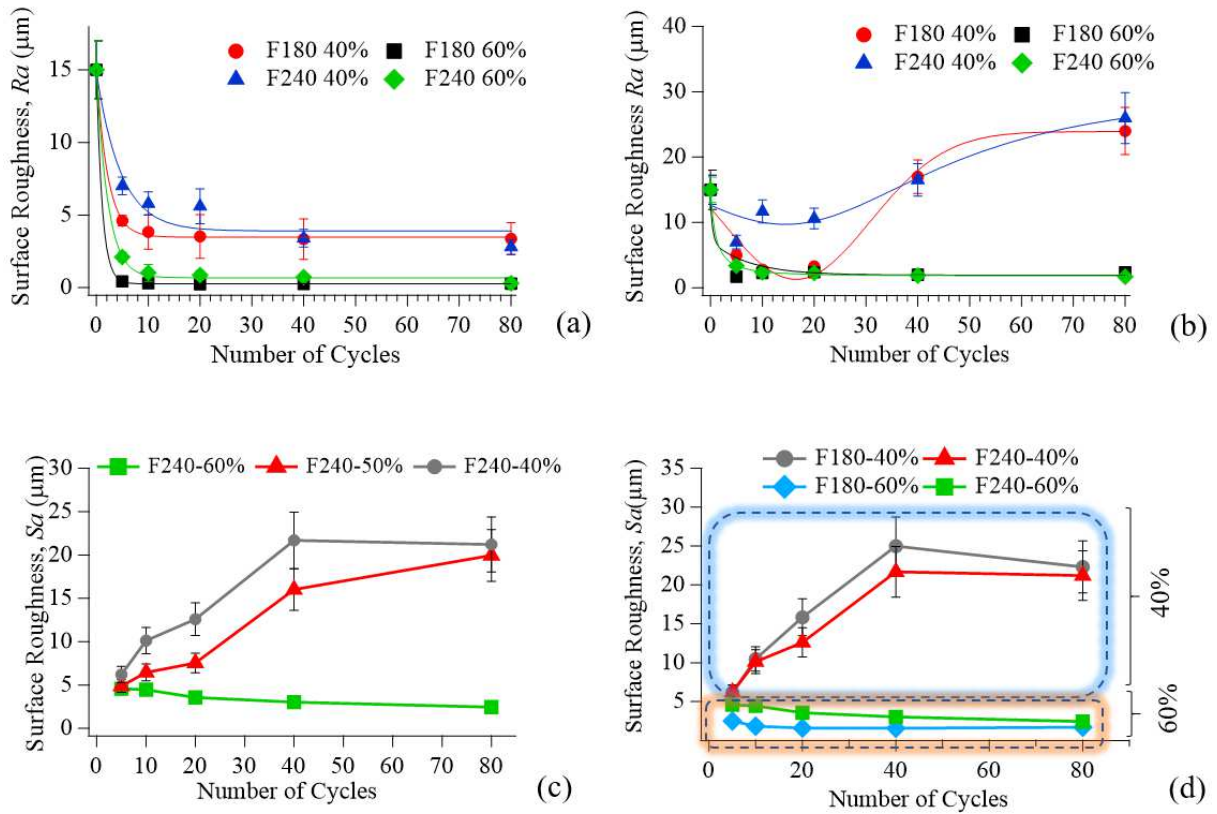


Fig. 8. Effect of SiC abrasive grain size and abrasive media concentration on surface roughness: (a) Ra roughness measured parallel to the flow direction, (b) Ra roughness measured perpendicular to the flow direction, (c) Sa roughness at various abrasive media concentrations, and (d) Sa roughness for various abrasive grain sizes and abrasive media concentrations.

In terms of Sa , the F180 abrasive yielded better results than F240 after five processing cycles. However, after 80 processing cycles, both abrasives achieved comparable surface quality. Because F180 has a coarser grain size than F240, it produces a higher material removal rate (MRR). Figure 9 shows the effect of abrasive grain size on the material removal rate. After five processing cycles, at the same abrasive media concentration, the F180 abrasive medium produced a higher MRR than F240. The same trend was also observed after 80 processing cycles, where the MRR was approximately eight times higher. While the AFM process improves the surface quality of the internal channels, excessive MRR can adversely affect their dimensional accuracy. An increase in channel diameter may alter the flow characteristics and flow rate of the working fluid. Therefore, rather than using the coarse-grained F180 abrasive to achieve rapid material removal, a more effective approach may be to perform a controlled AFM process using the finer-grained F240 abrasive, which provides comparable surface quality while minimizing material removal.

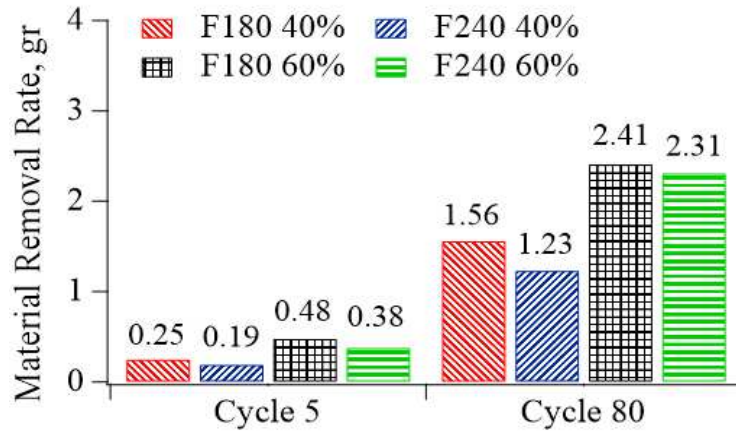


Fig. 9. Effect of AFM process parameters on the material removal rate (MRR).

The effect of AFM on surface morphology was examined using scanning electron microscopy (SEM) images. Figure 10a shows SEM images obtained using F240 SiC abrasive at abrasive media concentrations of 40% and 60%. No unmelted metal particles remaining from the additive manufacturing process were observed after AFM. The observed surface undulations and groove-like features correspond well with those observed in the optical microscope images at a 40% media concentration. However, a highly uniform and smooth surface was obtained at a 60% media concentration, and the resulting surface closely resembles that of conventionally cold-drawn materials. At higher magnifications, it is possible to observe submicron-scale scratches caused by abrasive particles. Notably, abrasive scratches were also observed deep within the surface grooves at the 60% media concentration. The abrasive medium hardens under high pressure and behaves similarly to a grinding wheel. Therefore, the formation of these grooves is directly associated with the abrasive media concentration and abrasive grain size.

The effect of abrasive grain size on the surface after AFM at an abrasive media concentration of 60% and 80 processing cycles is shown in Figure 10b through SEM micrographs. Both abrasive grain sizes produced similar surface morphologies. Since F180 consists of coarser abrasive particles than F240, the resulting surface scratches are more pronounced. Overall surface quality is governed by the abrasive grain size, the severity of abrasive-induced scratches, and the residual porosity associated with the PBF-LB process.

The relationship between abrasive particles, which generate scratches on the surface, and unmelted particles is illustrated in Figure 11 and described by Eqs. (3) and (4) [26]. In this model, the abrasive particle is assumed to be spherical with a diameter of d_g moving at a velocity, v , through an indentation depth, i . The interaction generates a normal force, F_n that

promotes material removal along the flow direction. Here, σ_r denotes the normal stress acting on the abrasive particle.

$$F = \sigma_r \frac{\pi d_g^2}{4} \quad (3)$$

or

$$F = H_e \pi \alpha^2 \quad (4)$$

Where α is the radius of the projected indentation area, and H_e is the effective hardness which considers not only the bulk hardness of the material, but also the local deformation behavior.

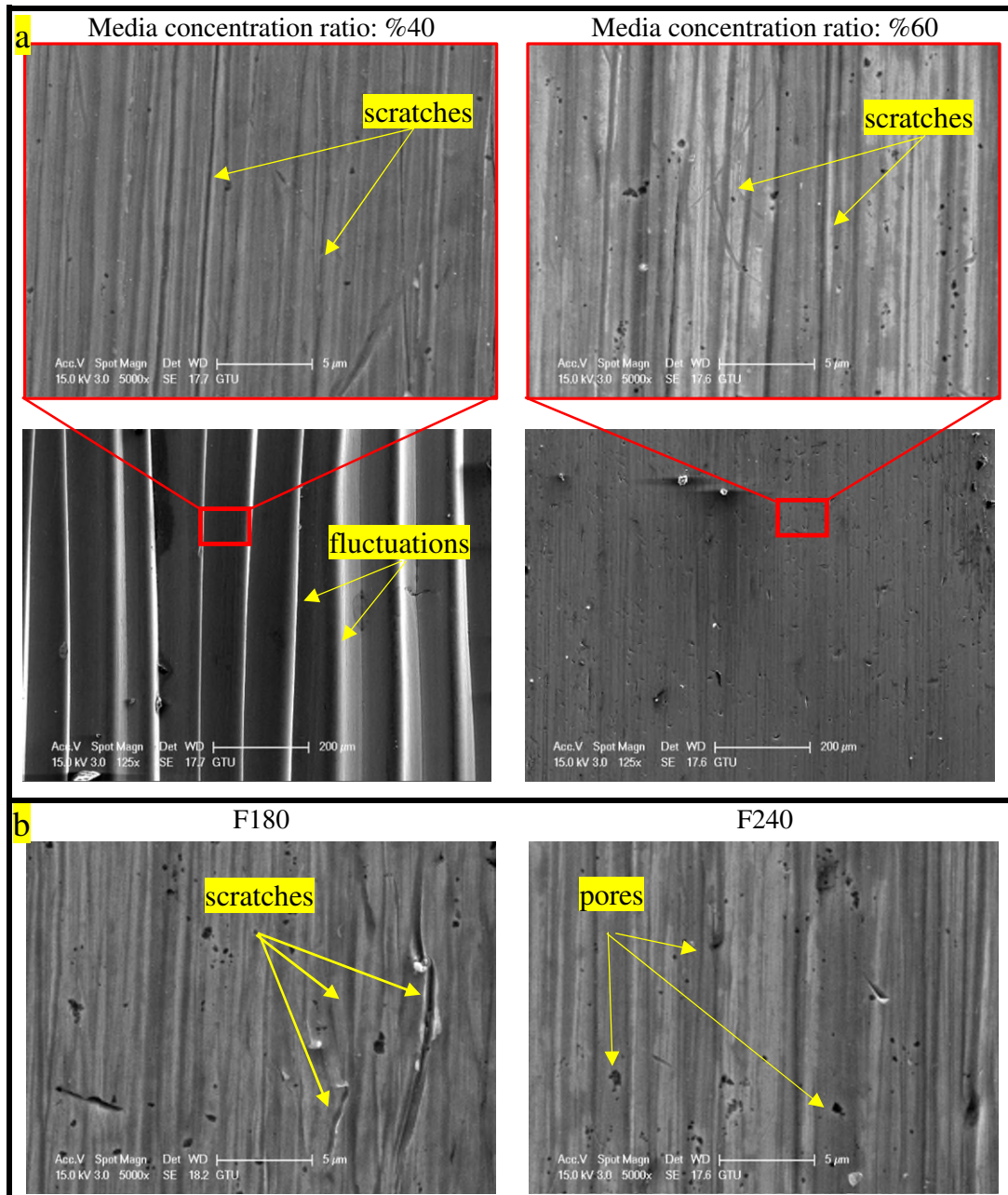


Fig. 10. (a) SEM images at 125× and 5000× magnification (abrasive grain size: F240), and (b) SEM images showing the effect of abrasive grain size on the surface (abrasive media concentration: 60%) (80 processing cycles for all images).

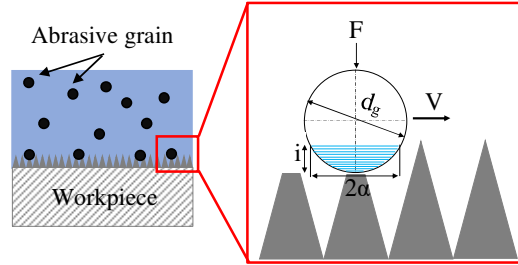


Fig. 11. Schematic representation of the AFM material removal mechanism.

3.1.2 Effect of heat treatment on surface roughness and topography

Figure 12 shows three-dimensional topographic images of the surfaces obtained after the AFM process of heat-treated Inconel 718 coupons manufactured for application purposes. The effect of heat treatment on the AFM process is evident starting from the first processing cycle. The presence of unmelted particles is greater on the as-built IN718-U surface than on the heat-treated IN718-U-HT surface. After five processing cycles, smooth surfaces were obtained, and the amount of unmelted particles was substantially reduced. After 10 processing cycles, the unmelted particles completely disappeared, but surface undulations began to appear. Thereafter, as the number of cycles increased, the surface undulations gradually developed into groove-like features.

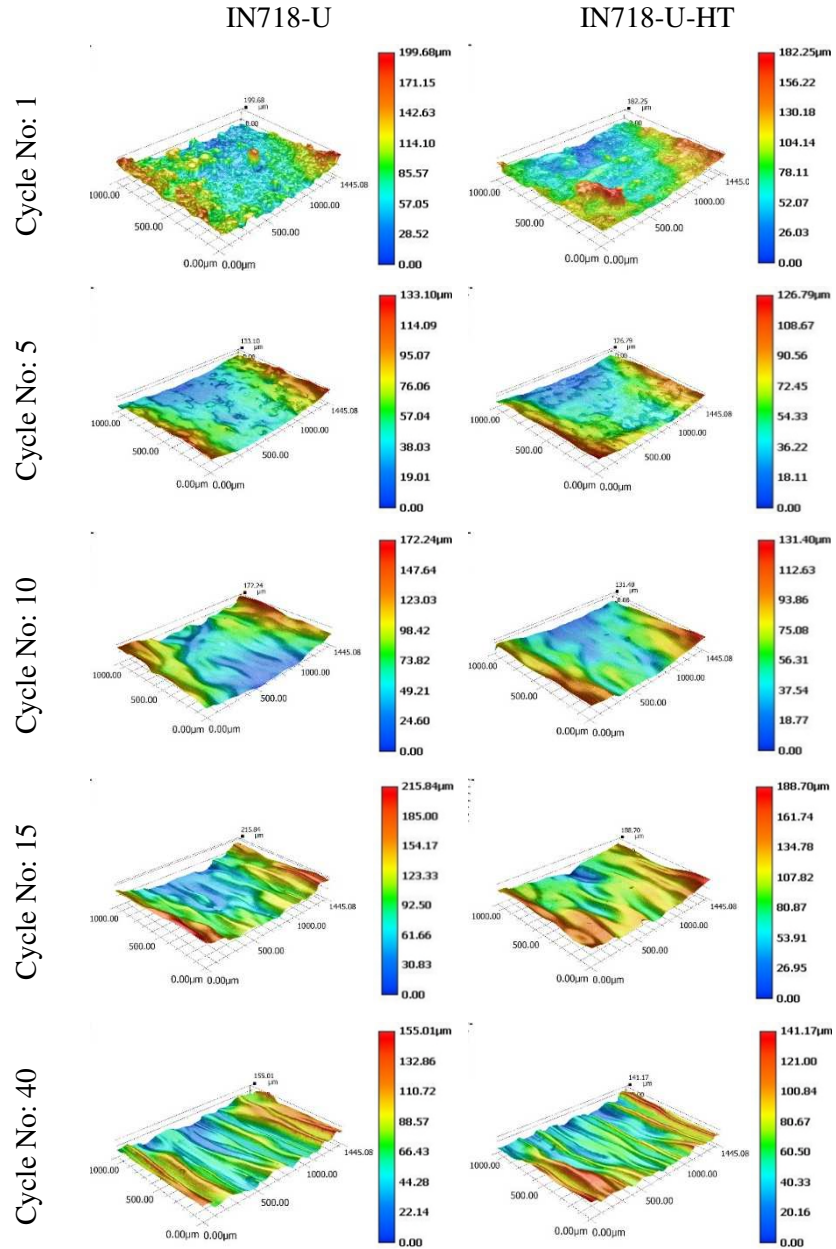


Fig. 12. Three-dimensional surface topography of heat-treated and as-built AFM-processed surfaces.

Figure 13 shows the areal surface roughness (S_a) values measured from the three-dimensional topographic images of the IN718-U and IN718-U-HT coupons. In general, the heat-treated specimens exhibited lower surface roughness than the as-built specimens. Heat treatment applied after PBF-LB directly affected the mechanical properties, microstructure, and other

surface characteristics of the components. Surface roughness decreased until the fifth processing cycle; however, further increasing the number of processing cycles resulted in surface deterioration and a subsequent increase in roughness. The lowest roughness value ($S_a = 4.13 \mu\text{m}$) was measured for the IN718-U-HT specimen after five processing cycles.

The angled geometry of the IN718-U specimens affected the flow of the abrasive medium within the channel. Instead of flowing through a straight channel, the change in flow direction around the angled features promoted the formation of surface undulations and pronounced grooves from the early processing cycles. Consequently, whereas surface roughness continued to improve with increasing processing cycles in the straight-channel specimens, the angled channel geometry reached its optimum surface quality after fewer processing cycles, beyond which additional AFM processing adversely affected the surface finish.

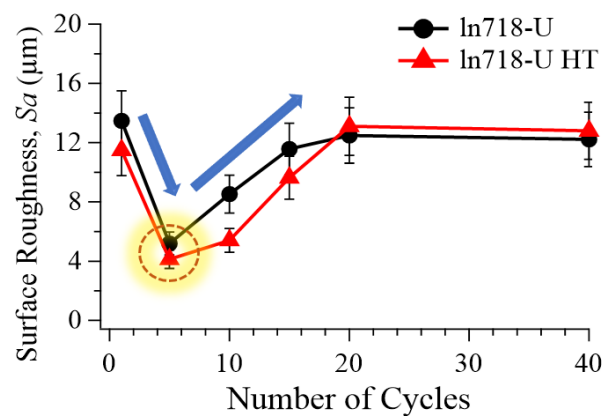


Fig. 13. Areal surface roughness of heat-treated and as-built AFM-processed surfaces.

3.2 Microhardness

The changes in microhardness of the AFM-treated surface resulting from different processing cycle numbers and abrasive media concentrations are shown in Figure 14a. No significant changes were observed in the microhardness values measured up to a depth of $500 \mu\text{m}$ below the AFM-processed surface. Specifically, at a depth of $15 \mu\text{m}$ below the AFM-processed surface, slightly higher hardening was observed after 80 processing cycles than after 5 processing cycles for both 40% and 60% abrasive media concentrations. However, considering the small differences in hardness values and the associated error bars, these variations were not statistically significant. Furthermore, the microhardness measurements obtained from deeper regions demonstrated that neither the number of processing cycles nor the abrasive media concentration had a significant effect on hardness.

The effect of different abrasive grain sizes and processing cycle numbers on microhardness at a 40% abrasive media concentration is presented in Figure 14b. For both abrasive grain sizes, the microhardness measured at a depth of 15 μm below the machined surface was slightly higher after 80 processing cycles than after 5 processing cycles. However, considering the small differences in hardness values and the associated error bars, it can be concluded that the AFM process has only a negligible influence on the microhardness of the machined surfaces, regardless of the AFM processing parameters. This observation is further confirmed by the measurements obtained up to a depth of 500 μm below the AFM-processed surface. Figure 15 illustrates this finding in detail. It presents optical microscope images of the Vickers indentation marks produced during the microhardness measurements. The indentation diagonals measured at depths of 15 μm and 500 μm below the machined surface were nearly identical, indicating that no significant variation in hardness occurred with increasing distance from the AFM-processed surface.

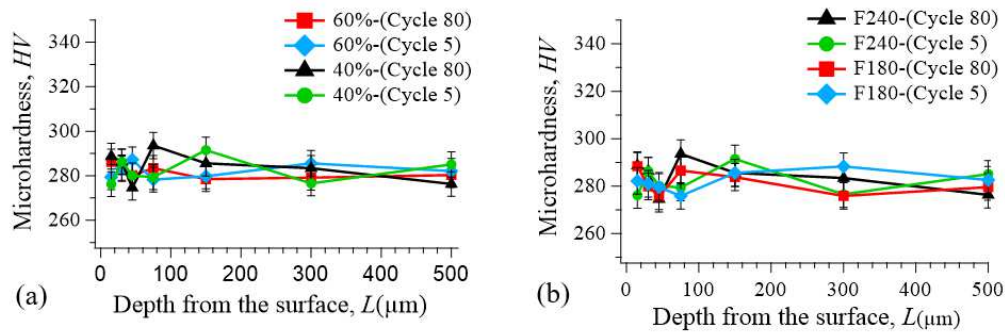


Fig. 14. Microhardness profiles showing the effect of (a) abrasive media concentration (F240 abrasive grain size) and (b) abrasive grain size (40% abrasive media concentration).

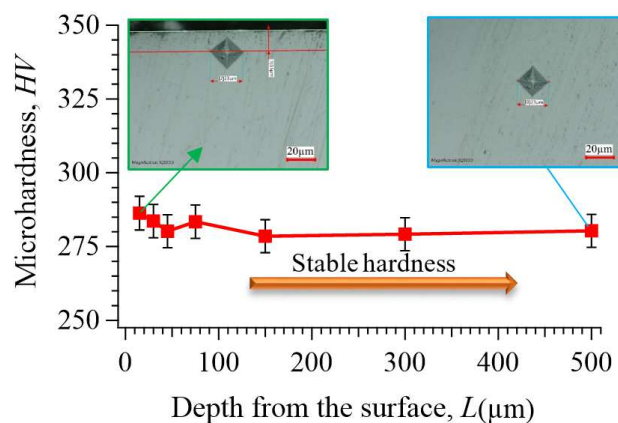


Fig. 15. Representative optical microscope images of Vickers microhardness indentations (F240 abrasive grain size, 60% abrasive media concentration, 80 processing cycles).

3.2.1 Effect of heat treatment on microhardness

Heat treatment is a process that directly affects many surface integrity characteristics of materials, such as the microstructure, microhardness, and porosity. Therefore, subjecting additively manufactured components to heat treatment before AFM requires investigation to determine how the heat-treatment-induced changes in the material affect their subsequent response to AFM. Figure 16 shows the microhardness values measured in heat-treated and as-built materials after 1 and 40 processing cycles. Heat treatment resulted in a decrease in the hardness of the coupons produced by AM. As observed in the previous AFM experiments, increasing the number of cycles did not lead to significant differences in microhardness. This trend was also observed in the heat-treated samples. Therefore, the AFM process applied after heat treatment of additively manufactured Inconel 718 components did not cause a significant change in the microhardness values obtained after heat treatment.

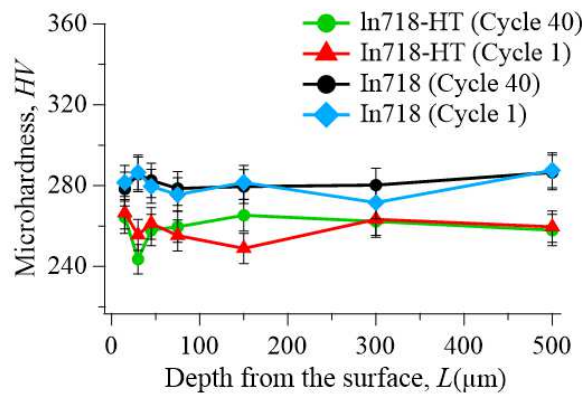


Fig. 16. Effect of heat treatment on the microhardness profile (F240 abrasive grain size, 60% abrasive media concentration).

3.3 Sliding Wear

Figure 17a presents the coefficients of friction obtained during the wear tests performed after the AFM process. The as-built sample exhibited a low coefficient of friction from the outset. The effect of poor surface quality was clearly observed. Partially melted Inconel 718 powder particles resulted in a low coefficient of friction because they reduced the stability of the sliding contact. After approximately 500 s of sliding, the coefficient-of-friction curve stabilized. This

was attributed to the removal of the partially melted powder particles during sliding. The coefficients of friction obtained after AFM at 40% and 50% abrasive media concentrations were close to that of the as-built sample. The lowest coefficient of friction was observed at an abrasive media concentration of 60%. These results demonstrate a clear relationship between surface topography and the coefficient of friction. While a wavy surface topography was observed at 40% and 50% media concentrations, a more uniform surface quality was achieved at a 60% media concentration.

The effect of abrasive media concentration on the coefficient of friction can also be evaluated using the microstructural images. Melt-pool boundaries characteristic of the additive manufacturing process were clearly observed. These boundaries result from interlayer thermal cycling and directional solidification, revealing the direct influence of the manufacturing parameters and cooling rate on the microstructure. Optical microscopy revealed no subsurface plastic deformation, grain-structure distortion, or microcrack formation. This indicates that the AFM process achieved the targeted surface quality by reducing surface roughness without altering the subsurface microstructure. Some studies have reported the formation of a white layer on AFM-processed surfaces [24]. However, microhardness data are not available in these studies. Therefore, as discussed in the previous section, the absence of significant changes in hardness further supports this finding.

Figure 17b shows the effect of the number of processing cycles on the coefficient of friction. The as-built sample exhibited the highest coefficient of friction. The coefficient of friction was higher after 5 processing cycles than after 80 processing cycles. Better surface quality was achieved after 80 cycles than after 5 cycles. Therefore, the reduction in the coefficient of friction was directly associated with the improvement in surface quality achieved by AFM. Thus, the AFM process parameters not only improved the internal-channel surface quality but also influenced the tribological performance.

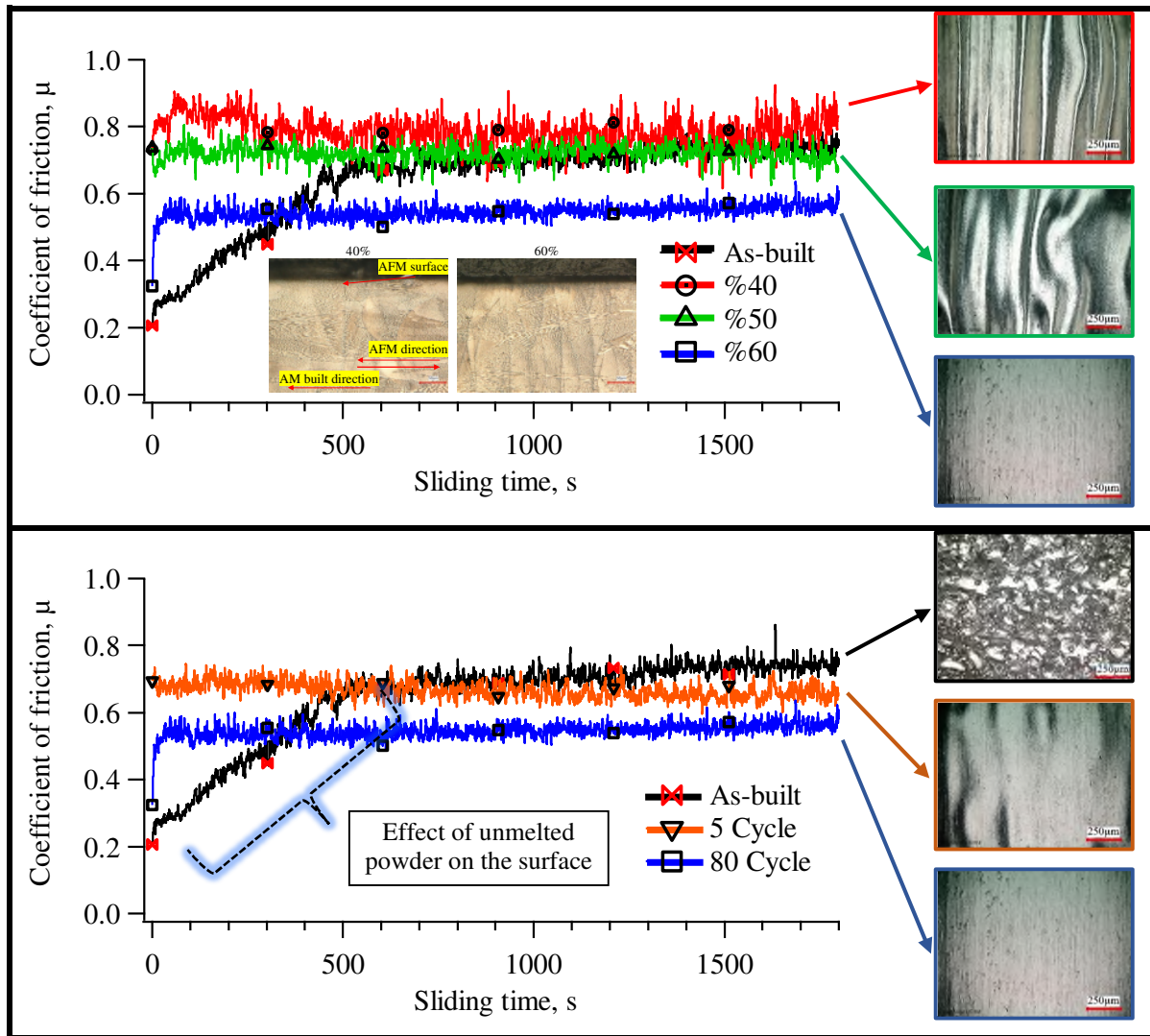


Fig. 17. Coefficient of friction: (a) effect of abrasive media concentration (80 processing cycles), and (b) effect of the number of processing cycles (F240 abrasive grain size).

4 Statistical Analysis

The effect of AFM process parameters on the experimental results was investigated using analysis of variance (ANOVA). This method enables statistical evaluation of the significance of each parameter by comparing its mean square value with the estimated experimental error at a specified confidence level. Table 2 presents the ANOVA results for the surface roughness (S_a) of AFM-processed IN718 holes. The p-value for the abrasive grain size parameter was greater than 0.05, indicating that its effect on surface quality was not statistically significant. In contrast, the p-values for abrasive media concentration and number of processing cycles were lower than 0.05, with contribution ratios of 55.4% and 22.1%, respectively. In particular, the dominant effect of abrasive

media concentration is consistent with the experimental results, because this parameter directly influenced the formation of surface undulations.

Table 2. ANOVA results for the areal surface roughness (S_a) of AFM-processed IN718 coupons.

Variance source	Degree of freedom (DOF)	Sum of squares (S)	Mean square (MS)	F-ratio (F)	P-value (P)	Percent (%)
Grain Size	1	0.04	0.035	0	0.966	0.003
Media %	2	785.89	392.947	21.17	0	55.4
Cycle	4	314.26	78.565	4.23	0.015	22.1
Error	17	315.51	18.56			22.2
Total	24	1419				100

The mathematical model for surface roughness, in which abrasive grain size, abrasive media concentration, and the number of processing cycles were used as independent variables, is given in Eq. (5). The relationship between the process parameters and surface roughness was established using multiple linear regression analysis. In multiple linear regression analysis, an R^2 value of 80% or higher generally indicates that the experimental data are well fitted by the regression model. Although the abrasive grain size parameter showed a negligible effect in the ANOVA analysis and the residual error accounted for 22.2% of the total variation, the regression model yielded an R^2 value of 78%, which is reasonably close to the desired threshold [27].

$$S_a = 34.19 + 0.0124\text{Grain Size} - 0.6216\text{Media Concentration} + 0.1147\text{Cycle Number} \quad R^2 = 78\% \quad (5)$$

Figure 18 shows the contour plot illustrating the relationship between the AFM process parameters and the areal surface roughness (S_a). Higher S_a values were observed at lower abrasive media concentrations, particularly as the number of processing cycles increased. In contrast, lower S_a values were achieved with fewer processing cycles when higher abrasive media concentrations were employed.

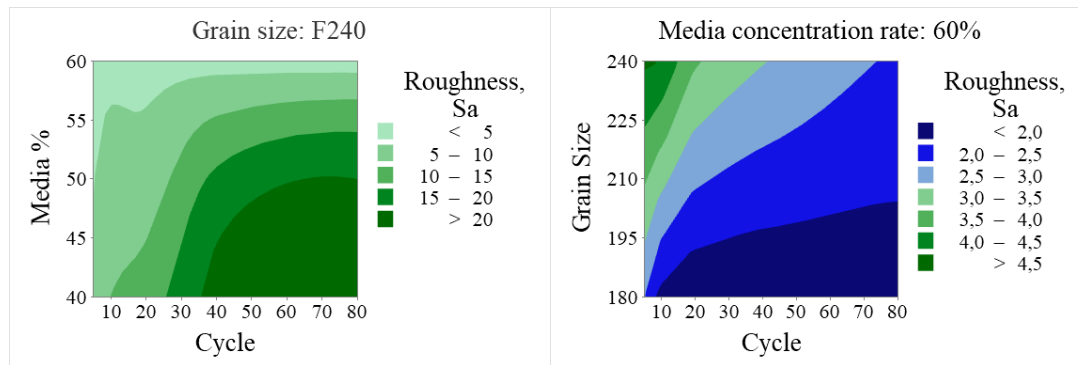


Fig. 18. Contour plot of the areal surface roughness (S_a) as a function of abrasive media concentration and processing cycle number.

5 Conclusions

This study investigated the effect of AFM process parameters on the surface quality of internal channels fabricated from Inconel 718 using powder bed fusion–laser beam (PBF-LB) additive manufacturing. Among the available post-processing techniques, AFM proved to be a highly effective method for improving the surface quality of internal channels. By eliminating unmelted powder particles from the surface, the AFM process achieved up to a 98% reduction in surface roughness while simultaneously improving the tribological performance of the machined surface through a reduction in the coefficient of friction.

The results further demonstrated that optimization of the AFM process parameters is essential for balancing surface quality and dimensional accuracy. Coarse abrasive particles produced the desired surface finish in fewer processing cycles; however, they also generated deeper micro-scratches and increased material removal, potentially leading to greater dimensional deviations. In contrast, finer abrasive particles required a larger number of processing cycles but provided a more controlled finishing process with improved dimensional stability.

More importantly, this study demonstrates that AFM is capable of significantly improving the surface quality of additively manufactured internal channels without compromising subsurface integrity. No significant changes in microhardness or microstructural damage were observed after AFM processing, confirming that the process effectively removes surface asperities while preserving the mechanical integrity of the material. Furthermore, unlike previous studies that primarily focused on external flat surfaces, this work provides a systematic investigation of AFM finishing for internal channels produced by PBF-LB, offering new insights into surface evolution, tribological performance, and process optimization for complex internal geometries.

Overall, AFM should be regarded not merely as a surface finishing technique but as an effective surface integrity enhancement process for additively manufactured internal channels. The findings provide practical guidelines for selecting AFM process parameters according to the required balance between surface finish, material removal, and dimensional accuracy. These results support the broader industrial implementation of additive manufacturing by enabling the production of conformal cooling channels with superior surface quality, preserved subsurface integrity, and improved tribological performance while avoiding the use of environmentally hazardous chemical finishing processes.

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Data availability

The data are available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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