Effects of Magnetic Abrasive Finishing on Microstructure and Mechanical Properties of Inconel 718 Processed by Laser Powder Bed Fusion

Yunhao Zhao 1, Jason Ratay 2, Kun Li 1, Hitomi Yamaguchi 2,* and Wei Xiong 1,*

1 Physical Metallurgy and Materials Design Laboratory, Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA 15261, USA; yunhao.zhao@pitt.edu (Y.Z.); kul17@pitt.edu (K.L.)
2 Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611, USA; jratay@ufl.edu
* Correspondence: hitomiy@ufl.edu (H.Y.); weixiong@pitt.edu (W.X.)

Abstract: Surface finishing is challenging in the context of additively manufactured components with complex geometries. Magnetic abrasive finishing (MAF) is a promising surface finishing technology that can refine the surface quality of components with complex shapes produced by additive manufacturing. However, there is insufficient study regarding the impact of MAF on microstructure–property relationships for additively manufactured builds, which is critical for evaluating mechanical performance. In this work, we studied the effects of different combinations of MAF and heat treatment steps on the microstructure–property relationships of Inconel 718 superalloys made by laser powder bed fusion (LPBF). The application of MAF was found to significantly reduce the surface roughness and refine the grain size of aged alloys. Moreover, MAF was able to increase the alloy elongation, which could be further influenced by the sequence of MAF and different heat treatment steps. The highest elongation could be achieved when MAF was performed between homogenization and aging processes. This work indicates that an effective combination of surface finishing and heat treatment is critical for the improvement of alloy performance. Furthermore, it demonstrates a promising solution for improving the performance of LPBF Inconel 718 by integrating MAF and heat treatment, which provides new perspectives on the post-processing optimization of additively manufactured alloys.

Keywords: magnetic abrasive finishing; microstructure evolution; mechanical property; laser powder bed fusion; Inconel 718

1. Introduction

Additive manufacturing is considered to be a promising solution in the context of fabricating structural metallic components requiring complex geometries and high dimensional precision. Meanwhile, the additive building strategy can reduce the waste of materials when compared with traditionally subtractive manufacturing, such as computer numerical control (CNC) machining, which removes materials from a bulk material. Despite the revolutionary merits brought about by additive manufacturing, there are still some issues accompanying the manufacturing process. One of the major problems is the high surface roughness of the materials processed by additive manufacturing, which can deteriorate the material’s performance [1–4]. Therefore, surface finishing technologies are necessary for additively manufactured components to improve their mechanical properties [5,6].

Magnetic abrasive finishing (MAF) technology has been developed for several decades for finishing the surface of workpieces with complex structures. The surface finishing is achieved by the relative motion between the workpiece and the magnetic abrasive, which is a mixture of magnetic particles and abrasive particles [7]. The unique processing features of MAF means that this technique has prominent advantages. First, it was found to effectively
reduce surface roughness to a range of 0.01~1 µm and to improve surface wear resistance [8,9]. Second, it can polish workpieces with uneven surfaces, such as straight or bent tubes [10]. Third, it can finish the internal surface of workpieces. Yamaguchi et al. [11,12] developed an internal MAF process for polishing the internal surfaces of components, and they applied it to the surface finishing of bent tubes made by Alumina ceramics and SUS304 stainless steels, demonstrating the potential of the wide application of MAF on various types of materials. They achieved a surface roughness of 0.02 µm for Alumina ceramic tubes and 0.03–0.04 µm for SUS303 stainless steels, with negligible additional residual stress introduced to the surface. Moreover, MAF technology can avoid the chemical contamination associated with other surface finishing methods such as chemical- or electro-polishing [13].

Because the surfaces of additively manufactured components are usually freeform and intricate [13], MAF technology can provide a promising solution for improving their surface quality. Multiple studies applying MAF on additively manufactured alloys have been reported. Yamaguchi et al. [6] reduced the surface roughness Rz of 316L stainless steels made by selective laser melting (SLM) to 0.1 µm, with the initial value being over 100 µm. An integrated polishing strategy was used by combining sanding, magnetic field-assisted polishing (MAP), and magnetic field-assisted burnishing (MAB). The authors found that both the MAP and MAB methods can introduce compressive stress on the workpiece surface and that the compressive stress magnitude imparted by MAB is much more than that by MAP, through which the surface stress can be transferred from tensile to compressive. In another work by Wu and Yamaguchi [14], the authors investigated the influence of the size and type of abrasive particles (i.e., either magnetic or conventional) on the mechanisms of the mechanical removal of materials and the resulting surface properties of SLM 316L stainless steel workpieces. It was concluded that finishing using magnetic abrasive particles can effectively refine the surface with a controlled material removal rate, in contrast with the traditional abrasive. Large abrasive particles mainly contribute to the removing of materials from the peaks of the surface geometry, whereas small abrasive particles can remove materials along the target surface features. Zhang et al. [13] investigated the MAF process on SLM 316L stainless steels components with different slope angles in order to simulate the shape effects of a typical workpiece on the finishing process. The MAF process was determined to effectively remove defects such as partially bonded particles and balling features and to reduce the surface roughness Rz with a maximum level of 75.7%. Substantial mechanical work was required within a considerable volume to achieve a successful polishing process. Teng et al. [15] polished SLM AlSi10Mg alloy by combining a grinding process and the MAF process and achieved a finest surface roughness of up to 0.155 µm. In addition, they concluded the MAF can reduce the surface hardness by removing shallow work-hardened materials and releasing internal energy, whereas an extended MAF process can maintain hardness values.

Inconel 718 Ni-based superalloy has been widely used in aerospace industries due to its good high-temperature mechanical performance and corrosion resistance [16–18], and it is popular among additive manufacturing communities due to its good printability [19]. The use of MAF technology for the surface finishing of Inconel 718 alloy has attracted interest from researchers. For example, Choudhary et al. [20] and Singh et al. [21] reported the successful surface finishing of Inconel 718 alloys using MAF with a final surface roughness between 0.046 and 0.254 µm. The processing time, pole rotational speed, and constituent of abrasive particles were found to be the major factors that affect finishing results. Kumar and Singh [22] investigated a chemically assisted MAF process on Inconel 718 workpieces. The chemical solution was reported to promote the finishing process, but they found that the effectiveness of the chemical solution with a certain concentration also depends on the processing time and constituents of the abrasive particles. In another piece of research conducted by Chaurasia and Wankhede [23], the effects of the process parameters of MAF on the surface roughness evolution of Inconel 718 was studied. The parameters optimized by Chaurasia and Wankhede [23] resulted in a surface roughness reduction of 87.1% compared to the initial condition and an Ra of 0.316 µm was obtained.
The working gap between magnet pole and workpiece was found to contribute the most to the surface finishing.

Despite this research on the application of MAF on Inconel 718 alloys, little work has been done in terms of the using MAF on Inconel 718 alloys processed by additive manufacturing. Meanwhile, while most of the reported work has only focused on the optimization of MAF process parameters or on the impact of the MAF process on surface structure and roughness evolution, whether MAF can also impact the interior microstructure and further impact the mechanical properties of materials remain unknown, especially when it comes to additively manufactured Inconel 718 alloys. Additionally, it is intriguing to reveal whether MAF process can cause different effects when applied together with heat treatment, which is an indispensible step for the post-processing of additively manufactured Inconel 718 alloys [24–26]. Consequently, the present work aims to study the influence of the MAF process on the microstructure and property evolution in additively manufactured Inconel 718. In this work, Inconel 718 components processed by laser powder bed fusion (LPBF) were subject to various sequences of heat treatment and MAF processes, and the microstructures resulting from different post-processing methods were characterized to determine the impact of MAF and heat treatment. Tensile testing was conducted to investigate the post-processing effects on mechanical performance. The process–structure–property relationships of LPBF Inconel 718 with respect to the MAF process were revealed and explanations for the underlying mechanisms were made.

2. Materials and Methods

The Inconel 718 alloys used in this work were built via the LPBF method by an EOS M 290 3D-printer (EOS company, Krailling, Germany). The Inconel 718 powder was produced by Praxair, Inc., Indianapolis, IN, USA, the nominal powder composition is listed in Table 1, and the nominal powder size is listed in Table 2. The printing parameters were the default values implemented in the 3D printer and were specifically designed for Inconel 718 alloys, which are listed in Table 3. The alloys were built as tensile bars with a dog-bone geometry according to the ASTM E8/E8M-16a standard [27]. The dimensions of the tensile bars can be found in Table 4. All the tensile bars were built horizontally with the long axis perpendicular to the build direction. The tensile bars were then subject to various post-processing conditions with different heat treatments and MAF processes. The sample/processing notations with corresponding processing conditions are summarized in Table 5. The homogenization process of 1180 °C-1 h is named as “H”, the aging process of 718 °C-15 h + 650 °C-10 h is named as “A”, and the MAF process is noted as “MAF” in the notations. The heat treatment was optimized from one of the authors’ unpublished works. When being heat-treated, the tensile bars were encapsulated in quartz tubes with a back-filled Ar atmosphere for oxidation resistance and were then quenched in ice-water when the heat treatment was completed. Figure 1 shows a schematic of the MAF finishing principle for flat Inconel 718 workpieces. A mixture of magnetic particles and abrasive is magnetized in the magnetic field, forms a particle brush along the lines of the magnetic field, and presses against the workpiece due to the magnetic force. When the magnet is rotated and translated, the particle brush is dragged by the magnet while conforming to the target surface. The relative motion of the particle brush against the target surface removes material and smooths the target surface.

Table 1. Nominal composition of Inconel 718 powder used in this work.

| Composition, wt.% | Ni   | Fe   | Cr   | Nb   | Mo   | Ti  |
|-------------------|------|------|------|------|------|-----|
| Balance           | Balance | 18.26 | 18.87 | 4.97 | 2.97 | 0.94 |
| Al                | 0.46 | 0.03 | 0.06 | 0.23 | 0.05 | 0.06 |
Table 2. Nominal powder size of Inconel 718 powder used in this work.

| Nominal powder size, μm | d10  | d50  | d90  |
|------------------------|------|------|------|
|                        | 18.5 | 20   | 44   |

Table 3. LPBF printing parameters of Inconel 718 used in this work.

| Laser Power | Scan Velocity | Hatching Space | Rotate Angle between Layers |
|-------------|---------------|----------------|-----------------------------|
| 285 W       | 960 mm/s      | 0.11 mm        | 67°                         |

Table 4. MAF experimental conditions.

| Magnetic particles | Abrasive | Lubricant | Magnet | Magnet revolution | Magnet feed | Clearance | Polishing time |
|--------------------|----------|-----------|--------|-------------------|-------------|-----------|----------------|
| G25 steel grit (C > 0.80%, S < 0.05%, p < 0.05%): 0.9 g | 126 μm mean diameter uncoated diamond abrasive: 0.1 g (additional 0.1 g added every 60 min) | Cutting fluid (Coolube® 2210EP): 0.4 mL (additional 0.05 mL every 2 min) | Nd-Fe-B magnet: Ø25.4 × 12.7 mm (3), Ø12.7 × 12.7 mm (1) | 600 min⁻¹ | 80 mm at 1 mm/s | 2 mm | 440 min (330 passes) |

Table 5. The notations of sample and processing conditions.

| Sample/Processing Notations | Processing Conditions |
|-----------------------------|-----------------------|
| H                           | 1180 °C-1 h           |
| H + A                       | 1180 °C-1 h + 718 °C-15 h + 650 °C-10 h |
| H + MAF                     | 1180 °C-1 h + MAF     |
| H + A + MAF                 | 1180 °C-1 h + 718 °C-15 h + 650 °C-10 h + MAF |
| H + MAF + A                 | 1180 °C-1 h + MAF + 718 °C-15 h + 650 °C-10 h |

Figure 1. MAF processing principle.

An experimental setup (Figure 2) was created, using a 5-axis CNC machining center, based on the processing principle. Table 4 shows the experimental conditions. A mixture of
0.9 g of G25 steel grit, 0.1 g of 126 μm friable wheel grit, and uncoated diamond abrasive (which enables more effective material removal than coated abrasive [28]) was used in the experiments with a set of Nd-Fe-B magnets (a Ø12.7 × 12.7 mm magnet centered on three Ø25.4 × 12.7 mm magnets). As the polishing progressed, a mixture of additional abrasive (0.1 g) and lubricant was added every 60 min. Under the specified experimental conditions, the magnetic force acting on the target surface (normal to the target surface) measured 2 N. The finishing pressure in the middle of the 6-mm-wide workpiece was therefore estimated to be 26.2 kPa. The linear path of the magnet began at the edge of the workpiece. The magnet was fed 330 times for a stroke of 80 mm at a feed rate of 1 mm/s. After finishing, the workpiece was rinsed with ethanol in an ultrasonic cleaner for further evaluation.

Figure 2. MAF polishing setup.

The surface roughness (Ra and Rz) of the workpiece surface was measured using a stylus surface roughness tester (Mitutoyo Surftest SJ-400, Mitutoyo Corporation, Kawasaki, Japan) before and after finishing to determine the effects of MAF on the surface quality. The roughness measurement points are shown in Figure 3. Since the samples were built horizontally, there were two different surfaces when the tensile bars were sectioned using an electric discharge machining (EDM) machine from the substrate, i.e., one printed surface and one EDM-cut surface. For the roughness measurement, scans with a length of 4 mm were conducted on both the printed and EDM-cut surfaces of each sample, as shown by red arrows in Figure 3, and the average values of the scans were calculated and used to represent the surface roughness on the particular surface.

The tensile tests were performed on an MTS Landmark Servohydraulic Test System using a strain rate of 1 mm/min. The fractography of the samples were characterized by a ZEISS-Sigma 500 VP SEM. EBSD (FEI Scios Dual-Beam system) characterization was performed on samples cut from the grip parts of the tensile bars after tensile testing to investigate the effects of MAF on the microstructure and to exclude the impact from the deformation caused by the externally-applied tension. In addition, it should be noted that the selection of the samples cut for EBSD characterization also ruled out the regions that may have been affected by the grip indents resulting from the tensile testing. A scan area of 3000 × 3000 μm and a step size of 5 μm were adopted for the EBSD mapping. The longitudinal planes parallel to the build direction were characterized.
using an electric discharge machining (EDM) machine from the substrate, i.e., one printed surface and one EDM-cut surface. For the roughness measurement, scans with a length of 4 mm were conducted on both the printed and EDM-cut surfaces of each sample, as shown by red arrows in Figure 3, and the average values of the scans were calculated and used to represent the surface roughness on the particular surface.

Figure 3. Images of the fully heat-treated samples before the MAF process (H + A) and after the MAF process (H + A + MAF): (a) printed surface before MAF and (b) after MAF; (c) EDM-cut surface before MAF and (d) after MAF.

3. Results
3.1. Surface Roughness after MAF

The MAF process was found to effectively improve surface quality and to significantly reduce the surface roughness of the heat-treated samples. The surface roughness of samples H + A and H + A + MAF were characterized as examples for surface quality analysis in this work. As can be seen from Figure 3, both the printed (Figure 3b) and EDM-cut (Figure 3d) surfaces became shinier after the MAF process, whereas before they were processed by MAF (Figure 3a,c), the oxides that formed on the surface during water quenching or EDM cutting made the surfaces lacking in luster. Table 6 compares the Ra and Rz values at different locations on each surface before and after the MAF process, which were demonstrated by red arrows in Figure 3. It can be found that the Ra and Rz at different locations on both surfaces decrease remarkably with the application of the MAF process. More specifically, on the printed surface finished by MAF, the average Ra is reduced from 2.0 µm to 0.46 µm and the Rz decreases from 11.0 µm to 2.47 µm, respectively. Similarly, on the EDM-cut surface processed by MAF, both the average Ra and Rz values decrease vastly (from 3.55 µm to 0.15 µm for Ra, and from 21.3 µm to 1.3 µm for Rz). The roughness measurement results show that the MAF process could reduce the surface roughness for both types of surfaces of LPBF alloys. The reduced values of Rz achieved after MAF indicate that the process could improve the surface roughness uniformity by reducing the maximum height differences between the surface peaks and valleys. It should be noted that although the average values of Ra (2.0 µm) and Rz (11.0 µm) of the printed surface are lower than that of the EDM-cut surface (Ra: 3.55 µm, Rz: 21.3 µm) before the application of MAF, they became higher (printed surface: Ra: 0.46 µm and Rz: 2.47) than their counterparts (EDM-cut surface: Ra: 0.15 µm and Rz: 1.3 µm) after being processed by MAF. This is because the printed surface...
was uneven as the surface was cyclically melted and printing textures were formed during the LPBF process.

Table 6. Surface roughness measurement results (in $\mu m$) of the fully heat-treated samples before the MAF process (H + A) and after the MAF process (H + A + MAF).

| Printed Surface | Left | Middle | Right | Average |
|-----------------|------|--------|-------|---------|
| Before          | Ra   | 1.53   | 1.76  | 2.7     | 2.0     |
|                 | Rz   | 10.3   | 8.7   | 14.1    | 11.0    |
| After           | Ra   | 0.34   | 0.40  | 0.65    | 0.46    |
|                 | Rz   | 2.1    | 2.4   | 2.9     | 2.47    |
| EDM-Cut Surface | Left | 3.33   | 3.8   | 3.51    | 3.55    |
|                 | Rz   | 19.7   | 21.4  | 22.7    | 21.3    |
| Before          | Ra   | 0.14   | 0.15  | 0.15    | 0.15    |
|                 | Rz   | 1.3    | 1.5   | 1.2     | 1.3     |

3.2. Microstructure Evolution

Figure 4 compares the effects of MAF and heat treatment on the microstructure evolution in LPBF Inconel 718 alloys. The grain size evolution is demonstrated by inverse pole figures (IPFs), as shown in Figure 4a1,b1,c1,d1,e1, and the average area-weighted [25] grain sizes of each sample were obtained from the EBSD characterization and are listed in Figure 4. The kernel average misorientation (KAM) values of each sample generated from EBSD are used to signify the change in internal strain levels [29] with different processes. The KAM values at each measured point are the average misorientation angles between the measured points and their surrounding neighbors [30]. The neighboring points within the 3rd kernel outside each measured point were counted in this work for the KAM calculation. A higher KAM level within one sample indicates that it is associated with a higher level of geometrically necessary dislocations [30] and thus implies a higher internal strain level. Because the KAM mainly reflects the localized strain level within one sample, the average KAM value is not adopted in this work for microstructure analysis; alternatively, KAM maps are provided in Figure 4a2,b2,c2,d2,e2 to illustrate the local strain distribution. Moreover, grain boundary maps obtained from EBSD are presented in Figure 4a3,b3,c3,d3,e3. The grain boundary density (GBD) is used to evaluate the grain boundary evolution with respect to the MAF and heat treatment conditions [24], and the GBD values are shown in Figure 4.

A comparison of samples H and H + MAF (Figure 4a1,b1) indicates that the average grain size of the homogenized sample H was not changed after being processed by MAF. Accordingly, the GBD values of samples H and H + MAF are comparable (Figure 4a3,b3). However, the local strain level increased with the application of MAF, as shown in Figure 4a2,b2. For the homogenized sample H, the KAM level after aging in sample H + A was found to be comparable or slightly lower than its counterpart before aging, implying that the aging treatment did not introduce extra strain into the homogenized alloy. The subsequent aging process after homogenization could increase the grain size from 259 $\mu m$ to 294.7 $\mu m$, as displayed by Figure 4a1,c1, and the GBD value was reduced (Figure 4a3,c3). On the contrary, the grain size was reduced after aging when the homogenized sample was treated with MAF, as shown in the comparison of samples H + MAF (Figure 4b1) and H + MAF + A (Figure 4e1), of which the grain size values are 261.3 $\mu m$ and 225.4 $\mu m$, respectively. Such an observation indicates that the introduction of aging after the MAF process can lead to grain refinement in LPBF Inconel 718 alloys. In addition, the aging step after MAF can also help with reducing the internal strain, which can be found from the reduced KAM level of sample H + MAF + A (Figure 4e2) with respect to that in sample H + MAF (Figure 4b2). Nevertheless, performing the aging process after
homogenization without the MAF process did not significantly change the KAM level (Figure 4a2,c2).

![Microstructures analysis using EBSD maps of inverse pole figure (IPF), kernel average misorientation (KAM), and grain boundary density (GBD): (a1) IPF, (a2) KAM, and (a3) GBD of the homogenized sample (H); (b1) IPF, (b2) KAM, and (b3) GBD of the sample H + MAF (with the MAF process after homogenization); (c1) IPF, (c2) KAM, and (c3) GBD of the fully heat-treated sample (H + A); (d1) IPF, (d2) KAM, and (d3) GBD of sample H + A + MAF (with the MAF process after full heat treatment); and (e1) IPF, (e2) KAM, and (e3) GBD of sample H + MAF + A (with the MAF process between the homogenization and aging processes). The grain boundary angle scale is given on the right-hand side of figure (e3).](image)

For the aged samples which are illustrated by Figure 4c1,d1, the application of MAF was found to refine the grain size from 294.7 μm (sample H + A) to 234.4 μm (sample H + A + MAF). Figure 4c2,d2 shows a slight increase in KAM level, which was caused by the MAF process. Moreover, because the MAF conducted immediately after homogenization (sample H + MAF, as shown in Figure 4b1) did not change the grain size compared to that of the homogenized sample H (Figure 4a1), it can be concluded that grain refinement can be achieved when the MAF process is performed following the aging process rather than the homogenization process. Besides, the comparisons of KAM levels between samples H (Figure 4a2) and H + MAF (Figure 4b2) and between samples H + A (Figure 4c2) and H + A + MAF (Figure 4d2) all indicate an increase in KAM inside of samples due to the MAF process, which indicates that the MAF process can introduce strain into samples regardless of preliminary heat treatment conditions.

A further inspection on the grain boundary shows that the high angle grain boundaries (shown as a black line in Figure 4a3,b3,c3,d3,e3) is predominant in all samples, as illustrated in Figure 4a3,b3,c3,d3,e3. However, the low angle grain boundary (shown as a red line in Figure 4a3,b3,c3,d3,e3) fractions of each sample are close to 2%. Hence, the influence of the low angle grain boundary can be negligible. The increase in the GBD of sample H + A + MAF (Figure 4d3) compared with that of sample H + A (Figure 4c3) indicates that the MAF process mainly introduced high angle grain boundaries. Similar conclusions can be made by comparing samples H + MAF (Figure 4b3) and H + MAF + A (Figure 4e3), specifically that the aging process following the MAF process increases high angle grain boundaries.
3.3. Tensile Properties and Fractography

Tensile properties and fractography characterizations were performed on samples H + A, H + A + MAF, and H + MAF + A to investigate the influence of processing on the alloys. The engineering stress–strain properties of alloys with various processes shown in Figure 5 and Table 7 indicate that the MAF process performed after aging (sample H + A + MAF) achieved the highest yield strength of 1152.1 MPa and the highest ultimate tensile strength, up to 1340.4 MPa, both of which are slightly beyond the sample H + A (without the MAF process). Furthermore, the elongation was significantly improved from 14% for sample H + A to 19.8% for sample H + A + MAF (with the application of MAF). When MAF was performed between the homogenization and aging processes, i.e., for sample H + MAF + A, the yield strength and ultimate tensile strength were between that of samples H + A and H + A + MAF. However, the highest elongation was achieved in the case of sample H + MAF + A, which was up to 22.7% according to Table 7. The tensile testing results indicate that the MAF process can significantly improve the elongation properties of heat-treated LPBF Inconel 718 alloys and meanwhile slightly refine their strength properties. The MAF performed between homogenization and aging was found to result in the highest elongation, whereas the MAF performed after aging achieved the highest strength among the alloys.

Figure 5. Stress–strain curves of the fully heat-treated sample H + A (without the MAF process), sample H + A + MAF (with the MAF process after the full heat treatment), and sample H + MAF + A (with the MAF process between the homogenization and aging processes).

Table 7. Tensile properties of samples H + A, H + A + MAF, and H + MAF + A.

| Sample           | YS, MPa  | UTS, MPa  | Elongation, % |
|------------------|----------|-----------|---------------|
| H + MAF + A      | 1148.6 ± 1.8 | 1332.3 ± 2.6 | 22.7 ± 0.3    |
| H + A + MAF      | 1152.1 ± 1.5 | 1340.4 ± 2.3 | 19.8 ± 0.5    |
| H + A            | 1142.8 ± 2.1 | 1304 ± 3.2  | 14.0 ± 0.5    |

The fractography of the tensile samples displayed in Figure 6 shows ductile fracture features in all the three samples. The fractography of each sample consists of a shear lip region near the surface and a fibrous region inside of the sample. The shear lip region and fibrous region are divided by a notable boundary depicted by white dashed lines in
Figure 6a,c,e. The thickness of the shear lip regions in different samples are similar. The radial region is not observed in the samples, indicating the alloys have good plasticity. Ductile dimples in the shear lip regions are shown in Figure 6b,d,f, and the shape and size of the dimples are comparable among the alloys. The fractography characterization implies the MAF process does not significantly influence the fracture mechanisms of heat-treated LPBF Inconel 718.

Figure 6. Fractography of (a) the fully heat-treated sample H + A (without the MAF process) and (b) magnified area of sample H + A in the shear lip region; (c) sample H + A + MAF (with the MAF process after full heat treatment) and (d) magnified area of sample H + A + MAF in the shear lip region; and (e) sample H + MAF + A (with the MAF process between the homogenization and aging processes) and (f) magnified area of sample H + MAF + A in the shear lip region.

4. Discussion
4.1. Effects of MAF and Heat Treatment on Microstructure Evolution

The influence of MAF on the microstructure evolution is mainly related to the grain refinement and dislocation density change as described in Section 3.2. A refined grain size was obtained in both samples, H + A + MAF and H + MAF + A (Figure 4d1,e1), which means the combination of aging and MAF processes can effectively refine grains. On the contrary, performing only MAF process on the homogenized sample did not change the grain size, as shown in Figure 4b1, and the aging process without MAF could lead to coarse grains (Figure 4c1). The increase in KAM levels after MAF indicates such a process can introduce external energy and dislocations into the materials. Dislocation density changes reflected by the KAM level could be increased with the introduction of MAF. Such effects were observed in both the homogenized sample, H + MAF, (Figure 4b2) and the aged sample, H + A + MAF, (Figure 4d2), but the aging following the MAF process instead reduced the dislocation density, as shown in Figure 4b2,e2. Without the application of MAF, aging can cause a negligible amount of change to the dislocation density (Figure 4c2).

Although grain refinement was achieved in both samples, H + A + MAF and H + MAF + A, the mechanisms of the refinement for each sample were different. For sample H + A + MAF, the MAF process introduced after aging was shown to break existing grain boundaries obtained after aging (i.e., sample H + A) and hence formed new grain boundaries. The details of such a mechanism remains to be further studied. However, a reasonable explanation can be made, which is that the process was realized by the direct interaction of $\gamma''$ strengthening precipitates that were largely formed during the aging process, with the energy introduced during the MAF process. Since few low angle grain boundaries were observed, it can be deduced that the high angle grain boundaries were directly formed during the MAF process. For sample H + MAF + A, the grain refinement should have happened during the aging process because the grain size in sample H + MAF without aging remained at a high level. It can be assumed that the aging process after MAF
could release the energy which had been stored in the alloy, reflected by high a KAM level in sample H + MAF (Figure 4b2). The energy release process further created new grain boundaries in sample H + MAF + A by interacting with γ" precipitates that were formed during aging. The grains were thus refined. In addition, since the high dislocation density in sample H + MAF was reduced after aging, it can be inferred that the dislocations further interacted and contributed to forming new grain boundaries.

4.2. Effects of MAF on Tensile Properties

The low surface roughness achieved by the MAF process contributed to the improvement of the elongation property. The removal of surface defects, such as partially bonded particles, balling features, and oxides caused by the LPBF and EDM cutting processes, improved the uniformity of the materials and reduced potential stress concentration for cracking initiation and propagation. Additionally, the good elongation property could also be linked with the grain size refinement achieved in aged samples with MAF. Liu et al. [31] found that a decrease in the grain size of fcc/bcc metals can result in the improvement of uniform elongation when the grain size is larger than ~200 µm. From Figure 4c1,d1,e1, it can be seen that samples H + A + MAF and H + MAF + A (processed with MAF) have a smaller grain size than that of sample H + A (without MAF). Accordingly, Figure 5 shows that the samples H + A + MAF and H + MAF + A have higher uniform elongation than sample H + A, which agrees with the conclusions made by Liu et al. [31]. Therefore, it can be concluded that the improvement made to elongation in the samples processed with MAF is a result of the grain refinement effect. A further investigation into the MAF-processed samples indicated that the sample H + MAF + A had a slightly higher uniform elongation than that of sample H + A + MAF by an increment of ~1.4%, as can be seen in Figure 5, which could be attributed to the smaller grain size of sample H + MAF + A (225.4 µm) compared to sample H + A + MAF (234.3 µm). The total elongation of sample H + MAF + A (22.7%) is higher than sample H + A + MAF (19.8%), with an increase of 2.9%, which is larger than the difference between the uniform elongation values of these two samples. Thus, a further increase in elongation occurred after necking in sample H + MAF + A compared to sample H + A + MAF. Such a phenomenon may be explained by the lower stress/strain level inside of sample H + MAF + A (Figure 4e2). However, a more specific study could be further conducted to determine the underlying mechanisms. Moreover, whether the MAF process can further influence the phase transformations during heat treatment and can impact the mechanical properties accordingly remains a question and should thus attract further investigation.

5. Conclusions

• The MAF process can effectively reduce the surface roughness of as-built and heat-treated Inconel 718 alloys made by LPBF. Both the printed surface produced by LPBF and the EDM surface generated from cutting can be significantly smoothed with the application of MAF.
• The combination of MAF and heat treatment can significantly influence the microstructure and property evolution of LPBF Inconel 718 alloys. The MAF process can increase internal strain in the alloys, but a subsequent aging process can mitigate the strain level. MAF process applied together with the aging process can reduce the grain size and increase the grain boundary density of alloy. Such microstructure change can significantly improve the elongation property of LPBF Inconel 718.
• The order of the MAF and heat treatment processes is found to affect the microstructure and further influence the elongation property. MAF applied between homogenization and aging can result in the highest elongation, although the material’s strength is only slightly improved with the application of the MAF process.
• An optimized process involving the coupling of MAF and heat treatment is a promising post-processing strategy for additively manufactured alloys with improved performance. Based on this work, it is meaningful to identify an effective pathway for
integrating MAF and heat treatment for the post-processing of additive manufacturing components to achieve high-performance with improved manufacturing efficiency.

- In MAF, magnetic particles act as a polishing tool, and the particle motion is an essential element in controlling the material removal characteristics. Further study will include the effects of magnetic particle motion [32] on the refinement of the microstructure and the improvement of the properties of LPBF Inconel 718.

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