Role of Superficial Defects and Machining Depth in Tensile Properties of Electron Beam Melting (EBM) Made Inconel 718

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Since there is no report on the influence of machining depth on electron beam melting (EBM) parts, this paper investigated the role of superficial defects and machining depth in the performance of EBM made Inconel 718 (IN718) samples. Therefore, as-built EBM samples were analyzed against the shallow-machined (i.e., only removal of outer surfaces) and deep-machined (i.e., deep surface removal into the material) parts. It was shown that both as-built and shallow-machined samples had a drastically lower yield strength (970 ± 50 MPa), ultimate tensile stress (1200 ± 40 MPa), and ductility ($28 \pm 2\%$) compared to the deep-machined samples. This was since premature failure occurred due to various superficial defects. The superficial defects appeared in two levels, as (1) notches and pores on the surface and (2) irregular pores and cracks within the subsurface. Since the latter occurred down to 2 mm underneath the surface, shallow machining only exposed the subsurface defects to outer surfaces. Thus, the shallow-machined parts achieved only 68% and 8% of UTS and elongation of the deep-machined parts, respectively. This low performance occurred to be comparable to the as-built parts, which failed prematurely due to the high fraction surface voids and notches as well as the subsurface defects.

Keywords additive manufacturing, electron beam melting, failure analysis, Inconel 718, near-net shaped manufacturing

1. Introduction

The electron beam melting (EBM) process is one important powder-based additive manufacturing (AM) technique for producing metal components (Ref 1). In EBM, an electron gun generates an electron beam that is deflected by electro-magnetic coils in order to selectively heat and melt the powder particles layer by layer (Ref 2). Since there are no moving parts in the optics (as in laser-based processes), the beam can be moved at very high speed, which can deliver a high production rate. The entire process is carried out under vacuum to protect the filament and the molten material from oxidation. Also, EBM uses a high processing temperature which can deliver a component without almost any residual stresses, eliminating the need for post heat treatment (Ref 3). For Inconel 718 nickel-based superalloy, this processing temperature can be as high as $950\text{--}1050^\circ\text{C}$ (Ref 4). Each powder layer is deposited with a typical thickness of approximately $50\text{ }\mu\text{m}$ (e.g., for Ti-6Al-4V) or $75\text{ }\mu\text{m}$ (e.g., for IN718). After the deposition, each powder layer is exposed to a material-dependent heating cycle. For the

case of IN718, this can include a first heating across the entire layer, a second heating to selectively melt the desired locations based on the sliced model, and a third heating to maintain the high temperature of each layer before the next powder layer is deposited. This constitutes an extreme heating condition and leads to the formation of semi-molten powder particles. This can extensively sinter the powder particles to the side surfaces of the solid component. As a result, the as-built EBM surfaces are well-known to be rough and porous. These rough surfaces may require extensive post-machining, being particularly essential for critical and high performance components.

The common users of EBM components are medical and aerospace industries. Within the medical industry, commercially pure titanium, Ti-6Al-4V, and CoCr (Ref 5, 6, 7) are usual materials for net-shaped components. Commonly, no post-machining is applied here, since the rough surface of EBM samples can favor the biological compatibility of biomedical implants (Ref 8). However, aerospace applications demand smooth surfaces. Therefore, extensive material removal can be necessary to create a smooth finish. This extensive machining limits the so-called ‘direct manufacturing of net-shaped components’ and ‘on demand manufacturing’, which are supposedly the main advantages of EBM as an AM process. It is usual in literature to report the tensile properties (Ref 9, 10, 11) and fatigue properties (Ref 12, 13, 14) of EBM components after intensive machining, which does not represent the actual mechanical performance of as-printed EBM components. This has been done almost for all materials in literature which have been used in the aerospace applications, including titanium alloys, TiAl, stainless steel, and nickel-based superalloys (Ref 2, 4, 15, 16, 17, 18).

Among the nickel-based materials, Inconel 718 (IN718) is the most common superalloy to manufacture components for the turbine components in jet engines (Ref 19). This is due to its high temperature strength, creep resistance, and high corrosion

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resistance. This performance originates from a Ni solid solution matrix saturated with other elements such as Cr and Fe (called γ), embedding coherent, ordered phases of γ'' (Ni_3Nb) and γ' ($\text{Ni}_3(\text{Al}, \text{Ti})$) as precipitates (Ref 10). This complex microstructure results in high strength and hardness and so machining of such a material is difficult (Ref 20). The surface of as-printed EBM IN718 components is ~ 100 times rougher than conventionally machined parts, which necessitates an extra step of machining (Ref 21), particularly to improve the fatigue life of the components (Ref 12). Furthermore, it should be noted that the region near the surface, which can contain internal defects such as pores and cracks, has a dramatic influence on the mechanical performance of any AM metal component. This is because defects at or near surfaces act as more potent stress concentrators than equivalent defects in the bulk (Ref 12, 22). Therefore, for having any successful EBM material, the superficial regions and the embedded defects must first be studied and improved.

For Ti6Al4V, as the most common material for EBM, the tensile properties differences between the as-built and deeply machined samples have been investigated. As-built samples showed lower tensile performance compared to the machined parts due to poorer surface condition (Ref 23, 24). However, there is no published work to investigate the surface and subsurface effects on the tensile properties of IN718. Moreover, the effect of machining depth on the tensile properties is not yet known. For example, it is not clear if the tensile performance would be sensitive to the amount of material removed from the surface. Accordingly, this work refers to ‘shallow-machining’ and ‘deep-machining’ to describe the state of the machining depth. In this context, the shallow machining denotes only removal of the as-built surfaces and the contouring region of the printing process (which is normally less than 1.5 mm from the outer surfaces). In contrast, deep machining can be safe removal of the outer surfaces over 3 mm deep inside the material.

As mentioned, no protocol yet exists on how deep the machining should be to develop optimum mechanical properties. Also, there is no published work to investigate the role of superficial defects, which are defined as appearing on the surface and within the subsurface region (Ref 23, 25), on the tensile properties of IN718. Therefore, this work systematically investigates the effect of machining depth and superficial defects on the tensile performance (as the first milestone of mechanical qualification) of EBM made IN718 parts. Within this objective, the tensile properties of as-built and shallow-machined samples are evaluated and compared to those from deep-machined parts. The defects in different depths are analyzed and related to the performances and failures of the parts.

2. Experimental Procedures

Plasma atomized IN718 powder was supplied by AP&C (Canada) with a particle size in the range of 45–105 μm and an average size of $\sim 90 \mu\text{m}$ (Fig. 1a). The chemical composition of the powder is shown in Fig. 1(b). This powder was used in an Arcam A2X EBM machine with default process parameters (Table 1).

A stainless steel plate with 10 mm thickness and 170×170 mm area was used as the baseplate. An optimized support

Fig. 1 (a) Powder morphology and (b) powder composition of the used plasma atomized IN718 powder

structure of 3 mm height was built on the plate. Then, cubic samples ($20 \times 20 \times 20$ mm) and tensile bars (Fig. 2) were printed on top of the support structure, as shown in Fig. 2. For the first print, in order to control the impact of print locations on the base plate, the shallow-machined samples (Fig. 2a S1–S4) were spread on four corners together with the deep-machined components (Fig. 2a D1–D4). This tensile specimens were machined after printing for the mechanical testing (Fig. 2b). The effect of the location of the components on the build plate is negligible, according to mechanical tests. Therefore, the second print was designed without considering the location of components on the build plate, and samples that received the same machining treatment were placed next to each other. To compensate for the shrinkage due to the high working temperature, a scaling factor of 1.017 in each direction within the build plate (x - and y - axes in Fig. 2a) and 1.02 perpendicular to the build plate (z - axis in Fig. 2a) was used as machine manufacturer suggested. Materialize Magics V22.0 software was used to design the layout to rescale the samples and to generate support structures. The EBM control software was version 4, which was especially developed for nickel-based superalloys. Within this software, an advanced melting strategy was generated, as shown in Fig. 3.

In order to verify the performance of the default process parameters, the density of cubic samples (Fig. 2a C1–C7) in the as-printed condition was measured. Archimedes’ method was chosen to test the density of the cubes using a MC 210 P balance (Sartorius, Germany) and a YDK 01 density testing kit, according to ASTM B311-17 (Ref 26). The weighing liquid was deionized water, and the accuracy of the measured result was $\pm 0.01 \text{ g cm}^{-3}$. Seven cubes were tested, in order to explore the location effect of the scatter in density of the fabricated samples. Afterward, the topology of the as-built top surface for both cubic and round samples was examined using a Phenom ProX scanning electron microscope (SEM) (Thermo Scientific, US). The side surfaces were viewed, and the surface roughness was measured using an optical 3D measurement system, InfiniteFocusSL (Bruker alicon, Germany), since it is an appropriate device for the rough surfaces. While the machined surface was analyzed using the white-light interferometer, Zygo NewViewTM 7300 (Zygo, United Kingdom) which is more suitable for the smooth surface.

After these tests, the cubes were cut, ground and polished according to standard metallographic preparation procedures to a 1 μm finish. Vickers microhardness measurements were performed on polished cubic samples to analyze the properties of the contouring and hatching regions. This microhardness

Table 1 The applied process parameters in the machine setting

General	Accelerating voltage	Working temperature	Rotation angle/layer	Start hatching angle
Value	60 KV	1025°	~ 72°	0°
Contour	No. of contour	Order	Beam speed	Multi-spot offset
Value	1°/2 ¹ *	Inner to outer	540°/1000 ¹ mm/s	0.3°/0.2 ¹ mm
Hatching	Beam speed	Focus offset	Beam current	Line offset
Value	4530 mm/s	15 mA	15 mA	0.125 mm

*Note: 'o' and 'I' refer to outer and inner contour, respectively.

Fig. 2 (a) Printing layout of the parts made in this work. 'D', 'S', 'A', and 'C' are codes for 'deep machining', 'shallow machining', 'as-built', and 'cubic' parts, respectively. (b) Dimensions of the samples before and after machining. The solid line indicates the as-built testing samples (A1). The dash line identifies the designed dimensions of the shallow-machined samples (S1) which were machined off 1.3 mm in radius to remove the as-built surfaces and multi-spot contouring region. The centerline indicates deep-machined samples (D1) which were printed as bulk cylinders and then machined off for 6 mm in radius. (c) The schematic of the multi-spot contouring scanning strategy employed for this experiment

was carried out using Mitutoyo HM-200 indenter (Mitutoyo, Japan) with 100 g load and 15 s dwell time in successive distances from the outer surface (300 µm, 600 µm, 900 µm, 1.2 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 5 mm, 6 mm, 7 mm, and 8 mm from the surface).

Tensile tests were performed at room temperature using Materials Testing 4505 (Zwick/ Roell, Germany), with a cross-head speed of 10 mm/min. All the samples were tested without post-processing heat treatment. The nominal dimensions of the as-built, the shallow-machined, and the deep-machined samples are shown in Fig. 2(b). The EBM samples made with multi-spot contouring were machined to reach the dimensions of ASTM E8 13-a standard (Ref 27). For deep-machined samples, 6 mm in depth was machined off in the gage volume. In contrast, only 1.3 mm in depth was machined off for the shallow-machined parts (Fig. 2b). This value had been selected since it could successfully remove both surface roughness features and the

outer region belonging to the multi-spot contouring strategy without removing excess material. The grip regions of the tensile test pieces were made to 14 mm in diameter to fit the collets of the tensile testing machine. Fractography was performed to analyze the failure of the tensile specimens using SEM. Table 2 summarizes the density and mechanical analysis methodology applied for each sample.

The cross-sectional analysis was performed on both cubic and tensile specimens (both gripping and reduction sections) which were well polished following the same procedure as mentioned before. The same SEM was used to view the samples, and the program ImageJ (Ref 28) was used to estimate the volume fraction of the pores in the images. Microstructure samples were also taken from the gripping section of the tensile test specimens with 17 mm diameter (Fig. 4). Subsequently, the samples were etched for approximately 20 seconds at room temperature in waterless Kalling's reagent. The SEM was used to view the microstructures.

3. Results

3.1 Density Analysis

The average density of the cubes printed with contouring strategy was $8.13 \pm 0.01 \text{ g cm}^{-3}$. Wrought annealed samples supplied by special metals had a density of 8.19 g cm^{-3} (Ref 29). Therefore, the relative density of the cubes was ~99.3% of the reference value. These density measurements may be slightly underestimated, since water was used as the measurement medium: water has a high surface tension, which may lead to the formation of small air bubbles trapped on the surface of the samples (Ref 30). The distribution of the porosity is an important factor that is not reflected in the total relative density. Accordingly, further analysis was carried out to illustrate the type, distribution, and the effect of surface and subsurface defects.

3.2 Top Surface Analysis

Figure 5 demonstrates the top surface topology of the as-built parts without and with contour for both cubic and round slices. In general, there are three different types of defects on the top surface: i) a rough border with semi-molten powder particles attached, ii) surface voids near the border, and iii) defects in the subsurface region. The rough border is a well-known issue for the EBM process, which is attributed to the high working temperature and the excessive heating. The surface voids (Fig. 5a), observed on the parts without contouring, were located between the turning points of the hatching lines. As seen from Fig. 5(b), the contouring strategy

Fig. 3 The schematic of the melting strategy employed for this experiment. Step I is the multi-spot inner contouring, step II is the multi-spot outer contouring, and step III is the continuous hatching strategy.

Table 2 Summary of the number of samples used for different investigation methods

Investigation method	Density cube, with contour	As-built, no contour	Tensile parts		
			As-built, with contour	Shallow-machined	Deep-machined
Density	7				
Microhardness	3 (10 readings per sample)				
Tensile test	—	4	4	4	4

Fig. 4 Samples in as-built condition used for cross section analysis on both x - y section (gray) and x - z section (blue), cut from (a) density cube, and (b) as-built tensile bars

can considerably reduce the number of the surface voids. However, this created porosity within the subsurface region, particularly where inner contours were located.

3.3 Side Surface Morphology

Figure 6 shows the side surface morphology and roughness, R_t (maximum vertical distance between the peak height and the valley depth), measured on as-built, shallow-machined, and deep-machined samples. Multi-spot contouring reduces both the surface void fraction (SVF) and surface roughness (to $270 \pm 80 \mu\text{m}$ from $431 \pm 21 \mu\text{m}$) in Fig. 6(b) compared to Fig. 6(a). However, the as-built sample with contour still shows a rough surface (R_t with a maximum of $R_t \leq 350 \mu\text{m}$) with semi-molten particles stuck on the surface by sintering. This leads to many large surface voids (around 15% in area fraction). After machining, the surface was significantly smoother. Hence, the remaining SVF for shallow-machined (Fig. 6c) and deep-

machined (Fig. 6d) samples was greatly improved to 2.1% and 0.4%, respectively. Nevertheless, this also demonstrates that the SVF after shallow machining is still 5 times higher than that after deep machining, as observed in the form of remaining pores and cracks on the surface (Fig. 6c and 4g). This is despite the fact that mere surface roughness values are comparable after shallow machining and deep machining ($5.7 \mu\text{m}$ in Fig. 6g vs. $5.0 \mu\text{m}$ in Fig. 6f).

3.4 Subsurface Analysis

Although surface roughness has been a matter of concern (Ref 23, 24), subsurface defects in EBM manufacturing are rather neglected in the literature. This is despite the fact that elongated porosities in the contouring regions can influence the mechanical properties even more than rough surfaces (Ref 23, 25). Accordingly, Fig. 7 shows the cross section of the cubic and as-built tensile parts in the reduced section, near the edges within the x - y (Fig. 7a, c and e) and x - z (Fig. 7b, d and f) sections. As seen, within the subsurface a variety of defects including surface notches, cracks, spherical and irregular pores can appear on and beneath the EBM surfaces (Fig. 8). This is in such a manner that some high aspect ratio irregular pores are extended up to 1 mm between layers within the x - z section. These pores happened to embed residual powder particles, suggesting a lack of melting. Multi-spot contouring smooths the outer surfaces and reduces the notches on external surfaces, but results in a higher fraction of subsurface defects (Fig. 7c-d vs. Fig. 7a, b). However, it should be emphasized that these pores are formed in the x - y section of the cylinders (Fig. 7c), while the cubic samples are much denser in the x - y section (Fig. 7e).

Fig. 5 The topology of the as-built samples, (a) for the as-built cubic (top) and round (bottom) samples without contour and (b) as-built cubic (top) and round (bottom) samples with contour

Fig. 6 The surface topology of the as-built without and with contouring, shallow-machined, and deep-machined parts: (a–d) general view of the surfaces, (e–h) 3D construction and roughness of the surfaces

Furthermore, the surface void fraction is not a clear function of the EBM part size (Fig. 9a). However, subsurface defects after multi-spot contouring significantly decrease with increasing the EBM part sizes. Naturally, the surface and subsurface defects drastically reduce after machining. Still, machining to a depth of 1.3 mm does not fully smoothen the surface and eliminate the subsurface defects (Fig. 9b). Therefore, deeper machining is required to achieve higher quality parts.

3.5 Microstructural Analysis

Horizontal sections consist of equiaxed grains, while the vertical sections show a columnar grain structure (Fig. 10). The coarser grains in the inner contour indicate a lower local solidification rate. This is due to the hot interior, which slows heat transfer. In the outer contour, heat is readily lost by radiation from the outer surface. The region near the inner contour can contain multitude of defects (Fig. 10). For

Fig. 7 The superficial defects of as-built parts in (a) $x-y$ and (b) $x-z$ sections of cylindrical tensile parts without contour; (c) $x-y$ and (d) $x-z$ sections of cylindrical tensile parts with contour; and (e) $x-y$ and (f) $x-z$ sections of cubic parts

Fig. 8 The typical defects within the samples at the (a) outer surface and (b) within the subsurface regions

example, hot cracks can occur when the metal in the inner contour region solidifies, as the outer contour region and internal body can shrink in opposite directions. Also, porosity can form where the thermal shrinkage from solidification cannot be fed by liquid. This can occur due to an interruption in the melt pool.

3.6 Mechanical Properties

3.6.1 Microhardness. The microhardness of the density cubes, as shown in Fig. 11, increases with distance from the surface up to a distance of 1.2 mm from the border. Beyond that, the hardness decreases and stabilizes 2-2.5 mm beneath the surface. Overall, the variation of the hardness is attributed to the specifically employed multi-spot strategy, imposing different melting behavior for contouring and hatching regions. The contouring was applied before hatching by a rapid exposure to the electron beam. This generated rapidly melted and rapidly solidified overlapping spots, reducing the grain size. Despite the finer grains, the porosity and defects also formed between the adjacent spots, reducing the measured hardnesses. For example, just beneath the surface at the location of 300 μm , the hardness was around 10-20 HV lower due to this increased the presence of microporosity. In comparison, the melt pools during hatching step were located within the hot interior. This

Fig. 9 Border porosity fraction (BPF) and surface void fraction (SVF) on EBM samples with contouring according to (a) their sizes and (b) machining depth from the surface

Fig. 10 Microstructure of as-built samples with contouring, shown for horizontal and vertical sections. The vertical section shows columnar grains, as expected due to the directional heat flow in EBM printing. The defects formed in the inner contour are due to solidification and thermal shrinkage.

Fig. 11 The microhardness of the EBM cubic part made with multi-spot contouring along the depth

reduced the solidification rate and therefore increased the grain sizes (see Fig. 10), resulting in the lower hardness of the interior region.

3.6.2 Tensile Properties. All deep-machined parts exhibit similar behavior, where yield strength (YS) is 970 ± 50 MPa, ultimate tensile strength (UTS) is 1200 ± 40 MPa, and

elongation is $28 \pm 2\%$ (Fig. 12). These results are well comparable to other reports on EBM of IN718 (Ref 10, 31) and the ASTM F3055 on powder bed fusion of IN718 (recommending a minimum UTS of 980 MPa and a minimum elongation of 27% after stress relieving (Ref 32)). Despite this success, there are still a number of spherical pores remaining in the core of the material, which can perhaps slightly reduce the ductility of the as-built EBM parts in comparison with some wrought and casting samples (Ref 33). All the as-built samples underwent failure at a stress that was significantly lower than expected (i.e. a premature tensile failure). Multi-spot contouring led to a small improvement in tensile properties. The premature failure and the small differences in the mechanical performance are attributed to the high percentage of surface void porosity (SVF about 15.3% with contouring and 20.7% without contouring, Fig. 6) as well as border porosity (BPF about 3.0% in volume with and 1.7% in volume without contouring). After shallow machining, the performance remains unsatisfactory with the UTS of only 790 ± 110 MPa and elongation of less than 2%. This is significantly lower than the tensile properties of the deep-machined parts (Fig. 12b), indicating the need for deep machining in order to satisfy the standard ASTM F3055 (Ref 32).

Deep-machined parts break after a high deformation ($\sim 27\%$) with cup-and-cone ductile fracture (Fig. 13a). In comparison, as-built part without contour breaks prematurely only after 0.7% elongation. This can be attributed to cracks formed from the deep notches on the outer surface (Fig. 13b). While imposing multi-spot contouring can slightly improve the tensile properties of the as-built parts, the as-built parts with contour only achieved 68% in UTS and 8% in elongation of the deep-machined parts, due to porosity and many non-melted powder particles in the subsurface region (Fig. 13c). This leads to irregular porosity in the subsurface region (see Fig. 7), which causes the premature failure. After shallow machining, the defects and, therefore, the causes of failure remain the same. The only difference is that now the non-melted particles appear on the surface, since the material above them has been removed (Fig. 13d).

4. Discussion

4.1 Origin of Superficial Defects

Defects after EBM can be categorized as (1) surface with large notches (depth of 250-980 μm , R_t of ~ 270 -430 μm and

Fig. 12 Tensile properties of (a) as-built, shallow-machined, and deep-machined parts and (b) comparison of tensile properties between the parts with standard ASTM F3055

Fig. 13 Fracture surfaces after tension: (a) ductile cup-and-cone fracture in deep-machined samples; (b) as-built parts without contour showing the weakest behavior due to the deep notches on the outer surface; (c) as-built parts with contour showing a brittle behavior with porosity and a large amount of unmolten particles in the subsurface region; (d) shallow-machined parts exhibiting similar behavior as the as-built parts with numerous unmolten particles only this time near the outer surfaces

SVF of $\sim 15\text{--}20\%$) and (2) the high aspect ratio and irregular subsurface porosity in the contouring regions (Figs. 5, 6, 7, 8, 9). The rough surface originates from the excessive transversal melting and sintering of the coarse powder at high powder bed temperature (particles had a median diameter of $\sim 90\ \mu\text{m}$, and the powder bed temperature was $1025\ ^\circ\text{C}$ in the current study) (Ref 34). The poor surface finish is evident as bumps caused by

excessive melting and sintered semi-molten particles on the side surfaces (Fig. 5, 6). However, there is still a difference between the parts made with the contour and without (Fig. 5). For the parts without the contour (Fig. 5a), the hatching lines were remelted, while the whole area remained a bulk form reducing the cooling rate at the edges. This creates a greater chance for semi-molten particles to be attached on the surface.

Fig. 14 Schematic formation of defects (a) without and (b) with multi-spot contouring

In comparison, for the parts with contouring (Fig. 5b), the contouring strategy was performed before the hatching step, where the spots were quickly melted and solidified. Thus, a narrow gap may form between the contouring and the surrounding powders, resulting in a smoother surface with fewer semi-molten powder particles attached. It is also interesting to note that many previous studies have been dedicated to improve the surfaces by altering a variety of important design (Ref 8, 35, 36), material (Ref 37, 38), and processing parameters (Ref 39, 40). However, the alternations of these factors can only deliver a limited improvement, and hence, post machining is still an essential step for the important surfaces.

Figure 14(a) demonstrates the schematic for the formation of surface notches without a multi-spot contour melting strategy. As seen, the molten material at the border of the melting area, as the start and ending point of the hatching lines, can be solidified and shrunk inward. This inward shrinkage can leave irregular notches/gaps between the electron beam tracks at the outer surfaces. Since these notches penetrate into the part, they can drastically harm the mechanical performance of the material. Nevertheless, the subsurface defects in EBM are rather neglected, despite the fact that they can abundantly form as a result of multi-spot contouring strategy (Figs. 7 and 9). As schematically shown in Fig. 14(b), this strategy interrupts melting, which can lead to discontinuous shrinkage. As a result, irregular inter-beam spot pores can form, embedding many powder particles that were not melted (see Fig. 7). It is interesting to note that the subsurface defects were more located at the interface of contour and hatching (i.e., ~1-2 mm from the outer surface). This indicates that feeding from the melt within the regions where the hatching meets the multi-spot made solid contour has not been successful. To resolve this issue, the role of contouring strategies on superficial defects shall be investigated in a later study.

4.2 Influence of Superficial Defects on Performance

As seen from Fig. 7, the majority of the pores after multi-spot contouring are localized within 2 mm beneath the surface. Since multi-spot contouring can generate a better surface with fewer surface notches and a lower surface void fraction, it can slightly improve the tensile properties. However, the improve-

ment from this contouring strategy is very much inadequate for a quality part. After contouring, the subsurface porosity is approximately 3% compared to only 0.2-0.3% porosity in the core of the part (this heterogeneous distribution of porosity results in a density of approximately 99.3%). Therefore, removing the subsurface porosity will improve the density and the mechanical properties. However, machining to a depth of 1.3 mm failed to reach satisfactory mechanical properties above the ASTM standard (see Fig. 13). In fact, although a high percentage of the surface voids had been removed by shallow machining, some remaining subsurface defects were exposed to the outer surfaces when the material above them was removed (compare Fig. 6b, c). These act as crack initiation sites, as schematically shown in Fig. 12, since the defects have small radii of curvature and concentrate stress—an effect that is more influential when a defect lies on the surface, compared to in the bulk, according to classical fracture mechanics (Ref 23, 24). Although shallow-machined parts could not meet the required standard (Ref 32), deep machining completely removed the surface and subsurface defects and hence deep-machined samples showed satisfactory yield stress, UTS, and elongation above the ASTM standard (Fig. 12) (Ref 32).

It is interesting to note that the volume fraction of the subsurface defects was higher for smaller cross sections (Fig. 9a). This is due to the lower border curvature of the contour, which allowed a less interrupted shrinkage. As a result, the cubic parts with straight contours showed minimum subsurface porosity (~1.5 % in volume in Fig. 7e, f). Subsurface defects were also lower in the horizontal direction than the vertical section (Fig. 9a). This can be attributed to partially lateral heat transfer of the contour (stimulating tilted grains—Fig. 10 vertical section) compared to vertically downward heat transfer of the hatching (inducing columnar grains—Fig. 10 vertical section). In fact, the lateral heat transfer decreases the depth of the melt pool, hence it causes lack of fusion and generates more porosity along the z-section.

As found from this work, the superficial defects have a drastic influence on mechanical performance of the EBM made components. Therefore, hot isostatic pressing (HIP) should be able to reduce/eliminate the process-induced closed subsurface pores to partially improve the mechanical properties of the as-built parts (Ref 41). However, HIP may no longer close the surface-exposed pores/cracks after shallow machining. As a result, it is doubtful that HIP after shallow machining could improve the tensile properties. Nevertheless, in continuation, the effect of various contouring strategies on the superficial defects and microstructural features is being explored separately.

4.3 Developing an Effective Machining Protocol

Defects were formed in the component to a depth of 2 mm (Fig. 7). In agreement to these figures, the microhardness stabilized below this depth (Fig. 11) where the grain structure has also become consistent (Fig. 10). Accordingly, 1.3 mm machining to form a smooth surface is not adequate to fully remove the subsurface defects and achieve satisfactory mechanical properties (although it can reach a similar range of surface roughness values compared to the deep machining, as shown in Fig. 6g–f). Therefore, for achieving high performance in IN718 components manufactured using EBM under the conditions reported in this study, one may advise to machine off at least ~2.0 mm of critical load-bearing surfaces.

5. Conclusions

This work analyzed the effect of the superficial defects and the machining depth on mechanical properties of the IN718 EBM parts. It has been concluded that:

- In EBM, defects that caused mechanical failure appeared both on the component surface and in a region beneath the surface.
- As-built parts without contouring treatment contained the roughest surface with notches penetrating into the part and an extremely high rate of surface voids (~20%). Rupture could easily initiate from such notches and cause early failure of the tensile samples (UTS = 610 ± 20 MPa and elongation = 0.8 ± 0.2 %)
- As-built parts with a contouring treatment show a lower surface void fraction and surface roughness than non-contoured samples. However, the fraction of the component surface that exhibited voids remained very high (15%), as did the roughness ~270 μm .
- Beneath the surface of as-built components after contouring treatment, a region of up to 2mm contained a multitude of defects (1.2-3.5% depending on the sample size, shape and direction). This was attributed to discontinuous melting in the contouring treatment.
- The defects led to poor tensile properties of multi-spot contoured as-built parts (YS = 750 ± 35 MPa, UTS = 816 ± 20 MPa, and elongation = 1.5 ± 1 %).
- Post printing surface machining is required to remove defects.
- After shallow machining to a depth of 1.3 mm below the original surface, defects such as irregular pores and cracks were exposed to the surface. This generated 2.1% surface and 0.6-0.7% subsurface defects. This surface defect exposure still resulted in unsatisfactory mechanical properties (YS = 790 ± 110 MPa, UTS = 812 ± 147 MPa, and elongation = 1.4 ± 1.0 %).
- The subsurface defects were also related to the building orientation and geometry of the contours. In fact, the subsurface defects formed more extreme along the building direction and parallel to the curved contours.
- After 6 mm (deep) machining, no superficial defects remained.
- Deep (6 mm) machined samples reached above the required tensile properties of ASTM standard F3055, with a yield strength of 970 ± 50 MPa, a UTS of 1200 ± 40 MPa, and an elongation of 28 ± 2 %.
- Shallow machining can lead to a similar range of surface roughness values compared to the deep machining. Although surface roughness is normally the main assessment for surface machining, a wider range of superficial and near-surface defects should be taken into account to define an appropriate machining protocol. In the current case for EBM of IN718 using the commercial parameters, this work suggests a machining depth of at least 2 mm.

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