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Surface integrity in abrasive flow machining (AFM) of internal channels created by selective laser melting (SLM) in different building directions

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Abstract

Selective laser melting (SLM) can produce a conformal cooling channel that is widely used in the mold industry. However, SLM inherent rough surface can cause stress concentration, reducing the fatigue life of the mold. In addition to the surface roughness, residual stress can affect fatigue life. Therefore, it is necessary to improve surface integrity, such as surface roughness and residual stress, of the internal channels created by SLM. The internal channels ($\phi 3$ mm) are created by SLM in horizontal and vertical directions. As a counterpart of the SLM process, the internal channel ($\phi 3$ mm) is also made by the conventional process, such as electrical discharge machining (EDM) in a wrought bar. After internal channels are finished by abrasive flow machining (AFM), the evolution of the internal channel's surface integrity, such as surface roughness and residual stress, is investigated. The surface roughness of the horizontally and vertically SLM built as well as EDM generated channels are measured with a stylus. The initial surface topography of the SLM built channels differs significantly depending on the SLM building direction. The stylus measurement reveals significant improvement ($< 1 \mu\text{m Ra}$) in surface roughness of all internal channels after AFM. The residual stress on the internal surface channel is measured with X-ray diffraction (XRD). After AFM finish, the compressive residual stress in the AFM flow direction is found to be induced on the SLM built and EDM generated channels. Thus, AFM finish can be considered to be beneficial to the surface integrity of the internal channel created by SLM and EDM.

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Keywords: Selective laser melting, Abrasive flow machining, Surface integrity

1. Introduction

Additive manufacturing technology, such as direct metal laser sintering (DMLS) and selective laser melting (SLM) made it possible to create complex geometry used in micro cooling channels in the gas turbine [1] and conformal cooling channels in the mold [2]. The complicated cooling channels can be produced by SLM in different building directions. It is commonly observed that the SLM building direction affects the surface roughness [3]. The SLM inherited rough surface can cause stress concentration to initiate cracks, reducing fatigue strength of the parts. Thus, it is necessary to study the

surface integrity of the SLM built channels created in different building directions and AFM finished ones. Therefore, internal channels are produced by SLM in the horizontal and vertical building directions and finished by AFM. Maraging steel 300 is chosen as a specimen material because it is widely used in the mold industry. The surface topography evolution and residual stress induced by AFM in the horizontally and vertically built SLM channels are investigated. The EDM generated channels and their AFM finished ones are also produced to study the effect of the process on the surface integrity.

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Nomenclature

D	diameter of the internal channel (mm)
L	length of the internal channel (mm)
L_c	cut-off filter (μm)
R_a	surface roughness (μm)
σ_{xx}	residual stress in the direction of the internal channel (MPa)

2. Internal channels preparation

Fig. 1 presents the various manufacturing procedure investigated in this paper.

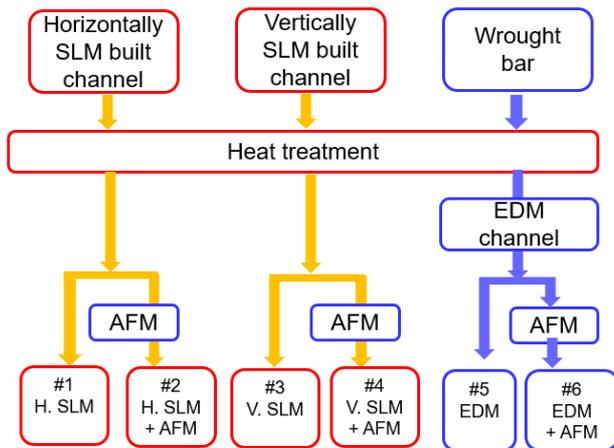


Fig. 1. Process flow diagram for fatigue specimens with internal channels.

The bars with an internal channel are generated by selective laser melting in the horizontal and vertical directions. Wrought bars are also prepared. After sintering process, all samples are heat-treated (470°C for 3h). The EDM process is a counterpart to compare a process to produce an internal channel with the SLM one. Electrical discharge machining (EDM) is used to generate an internal channel in the heat-treated wrought bar. The horizontally and vertically built internal channels were finished by AFM (case #2 and #4, denoted as H. SLM+AFM and V. SLM+AFM) and compared to SLM as-built specimens (case #1 and #3, denoted as H. AFM and V. AFM). The EDM generated channels were also finished by AFM (case #5, denoted as EDM+AFM) and compared to the EDM generated channel (case #6, denoted as EDM). Five specimens were made for each case so as to evaluate the deviation of each manufacturing procedure.

2.1. Horizontally and vertically SLM built, EDM generated internal channels

110-mm long bars ($\phi 15$ mm) with an internal channel ($\phi 3$ mm) were built in the horizontal and vertical directions by SLM process as shown in Fig. 3(a) (b). An SLM machine (EOS M270) is used for the SLM fabrication (hatching space 0.1 mm, layer thickness $40\ \mu\text{m}$). Powder grain size ranges from 20 to $50\ \mu\text{m}$. In case of the horizontally built SLM bar in

Fig. 3(a) the channel direction is perpendicular to the building direction. To avoid possible thermal distortion during SLM, a support structure is added to the bottom surface of the horizontally SLM built bar. On the other hand, in the vertically built SLM bar, the internal channel direction corresponds to the building direction as shown in Fig. 3(b). A through-hole ($\phi 3$ mm) was made in the wrought bar ($\phi 15$ mm) in one direction by die sink EDM as shown in Fig. 3(c).

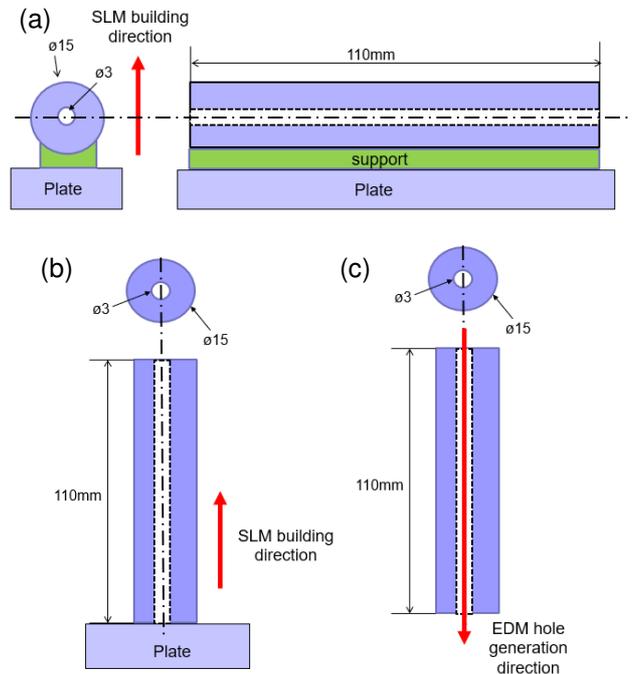


Fig. 2. The bars with an internal channel created by SLM in two building directions: (a) horizontally, (b) vertically, as well as (c) EDM.

2.2. AFM finish of SLM built and EDM generated internal channels

The SLM built and EDM generated internal channels were finished by AFM (case #2, #4, and #6 in Fig.1).

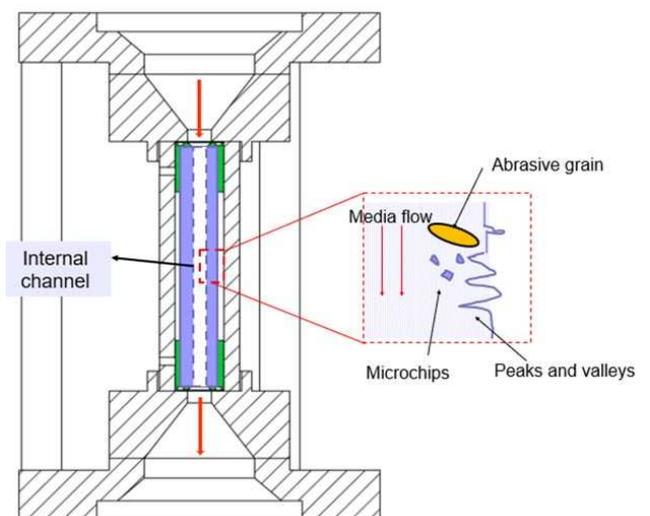


Fig. 3. (a) AFM finish of internal channels in the bar, (b) local material removal mechanism (cutting) in the channel surface by AFM.

The AFM process is employed to finish internal channels because it is shown to be effective for finishing of internal channels. A two-way AFM machine (Extrude Hone) is used for the AFM finish. The bar with the internal channel in the fixture is shown in Fig. 3. AFM media, in which silicon carbide (SiC) abrasive grains and polymer is mixed, flows through the internal channel. As shown in Fig 3, the abrasive grain contacts the rough channel surface and removes high peaks by cutting. The internal channel diameter of $D = 3$ mm is relatively small as compared to the relevant studies on AFM. Thus, AFM media, ULV50%-150 with very low viscosity is employed for the AFM. The grade of the AFM media represents ultra-low viscosity (ULV) and abrasive weight concentration of 50% and 150 grit size. The pressure of the AFM machine is set to be 80 bars. The AFM is performed for 20 cycles (about 180 minutes) at a media flow volume of 0.66 liter per cycle. The same AFM media was used for AFM of all samples. After AFM, surface integrity, such as surface roughness, residual stress, scanning electron microscopy (SEM) micrographs, and surface height map, of all internal channels is investigated in the next sections.

3. Surface integrity characterization of internal channels

3.1. Surface roughness measurement of internal channels before and after AFM

The surface roughness, R_a values of the internal channel surfaces before and after AFM was measured (ISO 4287). A contact stylus with a tip radius of $2 \mu\text{m}$ (Talyor Hobson, SB 211-2009) was used to measure the internal channel surface roughness. The measurement setup is shown in Fig. 4. The height of the stylus tip is about 2.3 mm to fit the channel diameter of $D = 3$ mm.

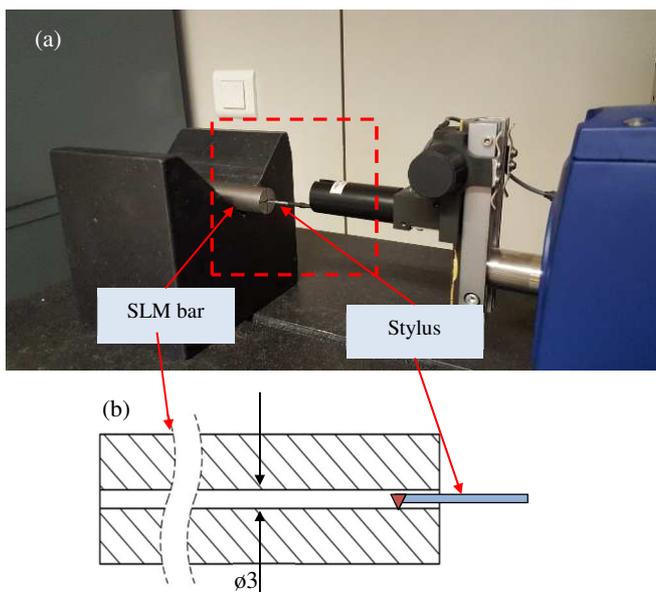


Fig. 4. Surface roughness measurement of the internal channel surface using stylus (Talyor Hobson): (a) set up, (b) cross section view of the SLM bar.

The stylus measurement was taken in the channel surfaces in both sides of the internal channel. A cut-off filter of $L_c =$

$800 \mu\text{m}$ was used to obtain R_a value. The scanning length is 5 mm. Surface roughness (R_a value) evolution of three types of internal channel surfaces before and after AFM are shown in Fig. 5. After AFM for 20 cycles, significant improvements in surface roughness from 5.2 to $0.3 \mu\text{m}$ R_a and from 5.6 to $0.2 \mu\text{m}$ R_a are seen on the horizontally and vertically SLM built channel surfaces. A significant reduction in surface roughness from 3.4 to $0.1 \mu\text{m}$ R_a is observed on the EDM generated channel surfaces.

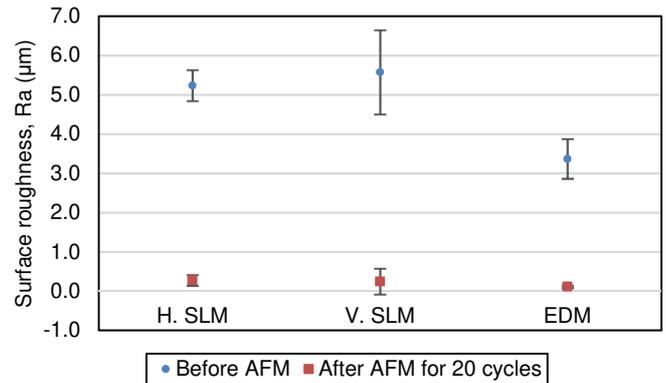


Fig. 5. Surface roughness (R_a value) evolution of three types of internal channel surfaces -horizontally built SLM, vertically built SLM, and EDM generated internal channels- before and after AFM.

3.2. Residual stress measurement on the internal channel surfaces

Residual stresses of all internal channel surfaces before and after AFM were measured with X-ray diffractometry (XRD). Detailed XRD measurement parameters were given in the previous study [4]. To measure residual stress on the channel surface, the specimens were cut by wire-EDM as shown in Fig. 6(a). This EDM sectioning can result in stress relaxation in the bulk of the specimens. Residual stress in the channel direction is denoted as σ_{xx} and indicated in Fig. 6(b). The measured residual stresses in the channel direction are shown in Fig.7.

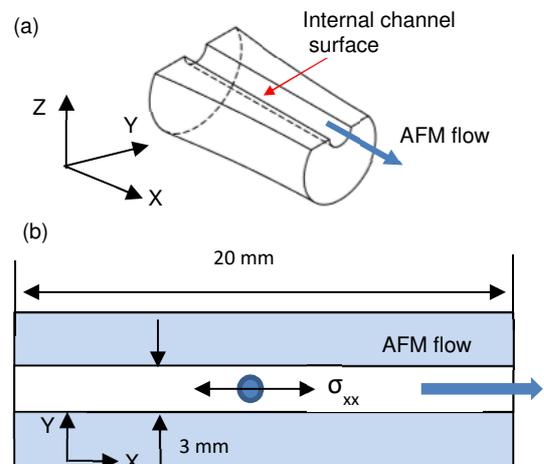


Fig. 6. Sectioning of the specimen for residual stress measurement of the internal channel surface: (a) 3D view and (b) XY cross section view to indicate XRD measurement location.

The vertically built SLM channel surface exhibits residual stress close to equilibrium. The residual stress in the SLM channel surface can be relaxed during heat treatment as shown in the process flow in Fig. 1. Tensile residual stresses ranging from 100 to 200 MPa have been observed on the surface cut by EDM [5][6]. Kruth et al. [6] found stress relaxation as a function of time on the wire-EDM cut surface. These phenomena can cause the residual stress on the EDM generated channel to be close to equilibrium. The residual stress on the horizontally built SLM surface was not obtained by XRD analysis. The horizontally built SLM surface shows a staircase shaped geometry produced during SLM. Thus, its geometry can result in the errors in the analysis of its X-ray diffraction pattern.

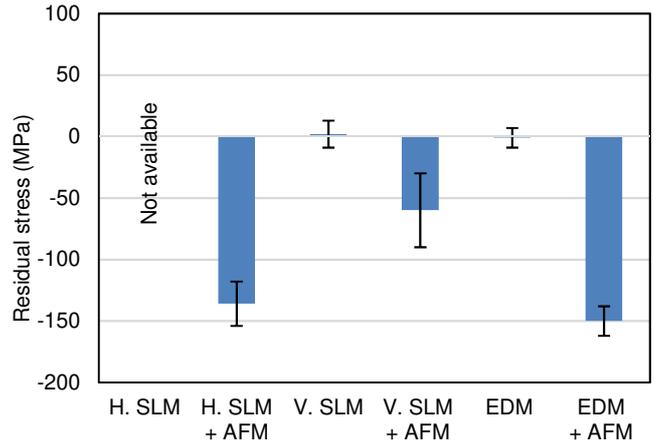


Fig. 7. Residual stresses in the channel direction of three types of internal channels before and after AFM.

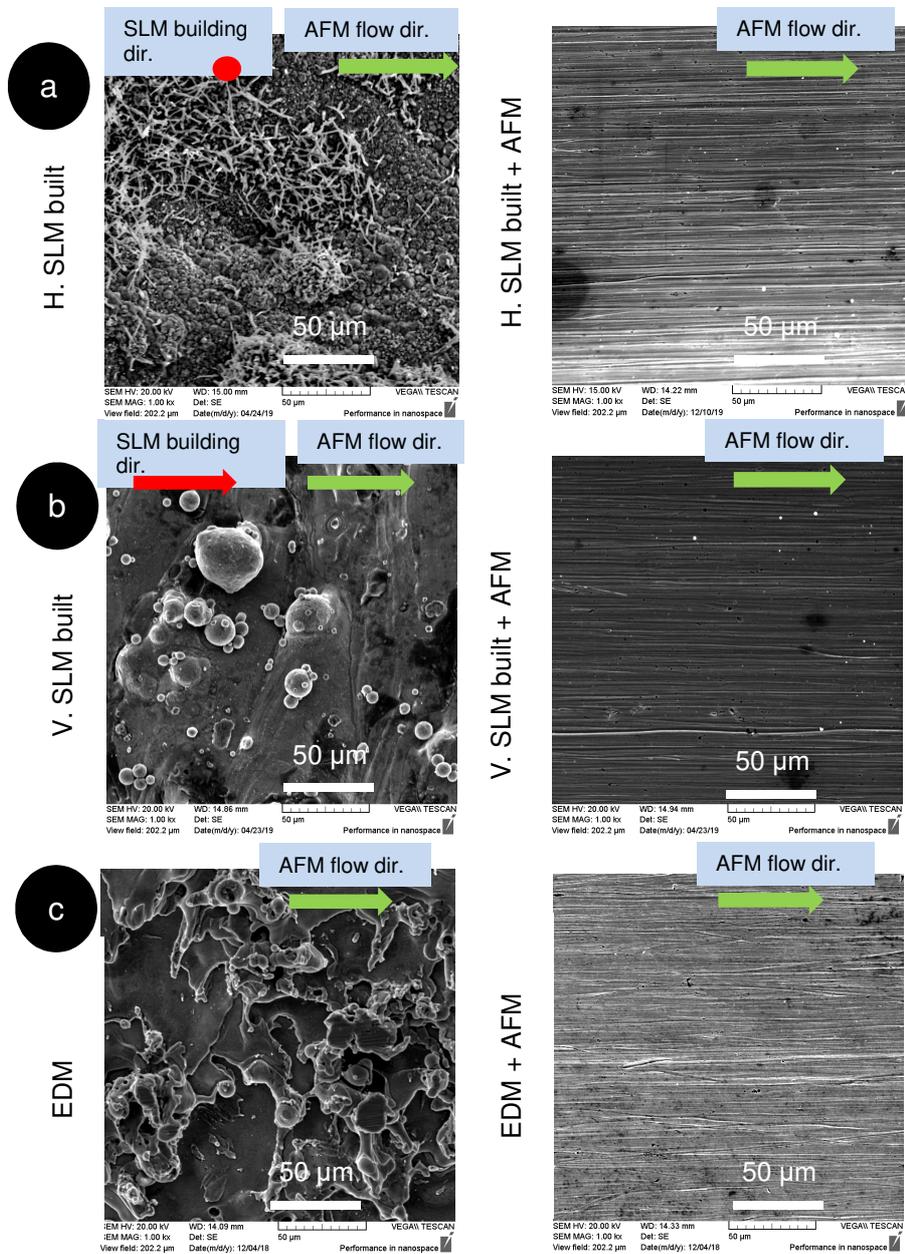


Fig. 8. SEM micrographs of three types of internal channel surfaces before and after AFM: (a) horizontally built SLM, (b) vertically built SLM, (c) EDM generated internal channels.

After AFM, in all internal channel surfaces, compressive residual stresses were observed. Increase in compressive residual stress is seen in both vertically built SLM and EDM generated channel surface. Similar trends have been reported in AFM finished surfaces. Kenda et al. [7] found that compressive residual stresses were induced in the hardened tool steel AISI D2 surfaces after AFM. Han et al. [8] reported that compressive residual stresses were induced in the AFM finished 15-5PH stainless steel channel surfaces. Compressive residual stress can be attributed to the plastic deformation induced under abrasive grains during AFM.

3.3. SEM micrograph of the internal channels

SEM micrographs of three types of internal channel surfaces before and after AFM were taken. They are given in Fig. 9. As shown in Fig. 9(a), a red dot represents the SLM building direction approaching to the view. The SLM building direction is perpendicular to the channel direction (See Fig. 1). The AFM flow direction, which is parallel to the channel direction, is indicated as an arrow. In Fig. 9(b), the SLM building and AFM flowing directions are indicated as arrows on the vertically built SLM channel surface. The vertically channel surface is parallel to the SLM building direction (See Fig. 1) and corresponds to the side walls of the SLM built parts. Local wavings, which is often seen in the side walls of SLM building surfaces, are visible. Partially melted powders are also seen on the surface. These irregular patterns were completely removed after AFM for 20 cycles. AFM flow marks were left on the surface. In Fig. 9(c), EDM generated channel surface reflects its material removal process. The channel surface was created by melting the surface by the

sparks of EDM electrodes and flushing it away. Remaining molten metals form the topographies of the EDM generated channel surface. The EDM generated surface also shows AFM flow marks after AFM. The SEM micrographs show that the SLM and EDM process inherited surface topographies were completely transformed into the AFM finished surface ones. The AFM finished surface topographies, which are characterized by AFM flow marks, are comparable with those in other studies [9][10].

3.4. Surface height map characterization

The surface height maps of internal channel surfaces were obtained by a focus variation microscopy (Infinite G5, Alicona). The cylindrical channel is designed and fabricated by SLM in this study. However, the cylindrical form in the horizontally built surfaces seems to be deviated. This deviation of the cylindrical form of the channel can be attributed to the staircase effect in SLM as illustrated in Fig. . On the other hand, the vertically SLM built channel surface shows a better cylindrical form than that of the horizontally built ones. The difference of the error of the cylindrical form between channels built by SLM in different building directions is similar to the finding of Snyder et al. [1]. Although surface roughness of the horizontally built surface decreased after AFM, the form still remains deviated from the original cylindrical form in Fig. 9(a). By contrast, the vertically SLM built channel after AFM shows a smooth surface with a better cylindrical form in Fig. 9(b). The EDM generated channel surface shows good cylindrical form before AFM and became smooth surface after AFM in Fig. 9(c).

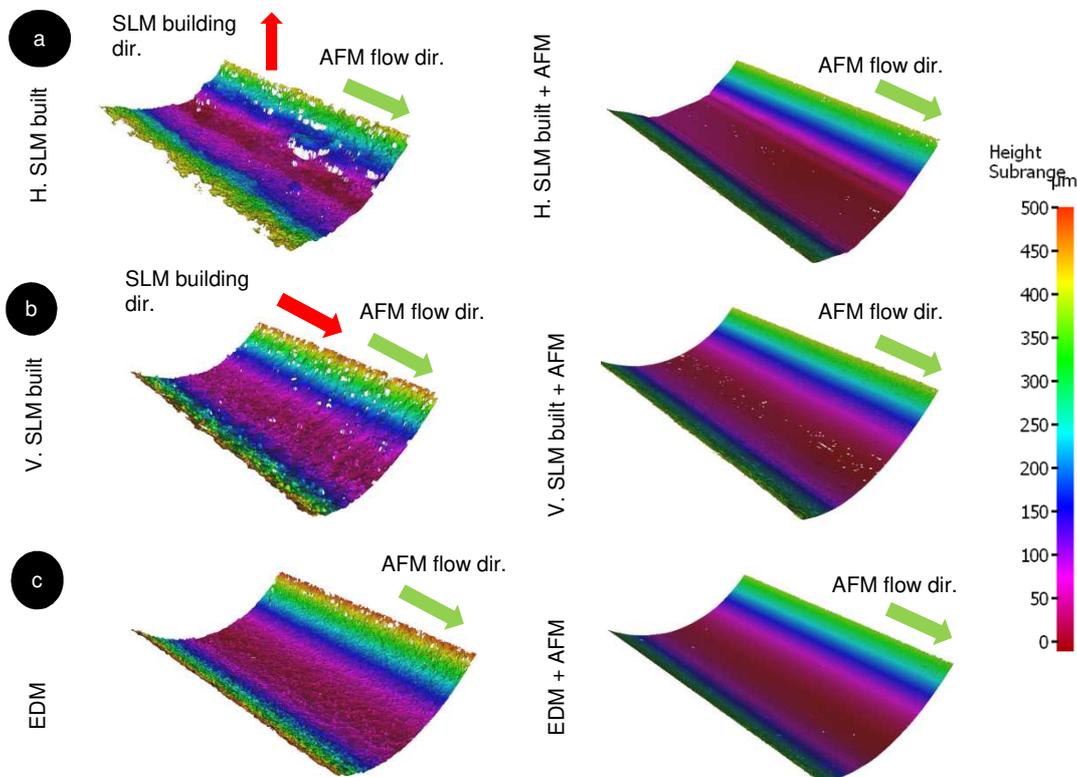


Fig. 9. Height map characterization of three types of internal channel surfaces before and after AFM: (a) horizontally built SLM, (b) vertically built SLM, (c) EDM generated internal channels.

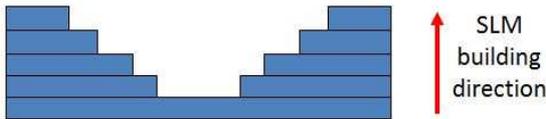


Fig. 10. Staircase effect on the horizontally built SLM channel surface.

3.5. Possible effects of the surface integrity of AFM finished channel surface on performance of the internal channel

As mentioned in the introduction and shown in Fig. 11, high surface roughness of the SLM built channel surface can cause crack initiation on its surface due to stress concentration.



Fig.11. Crack initiation due to high roughness of SLM built conformal channel surface (Courtesy of IPC).

AFM is shown to reduce surface roughness significantly and induce compressive residual stress on the internal channel surface. Thus, AFM process is expected to enhance fatigue performance of the internal channel. Related studies are underway. Also, AFM is found to be capable of polishing the internal channel with the ratio of $L/D = 120$ [11]. It can be used for internal channels with a higher ratio of L/D .

4. Conclusion

Internal channels in the bar were created by SLM in horizontal and vertical directions. The EDM generated internal channel in the wrought bar was added as a counterpart to produce an internal channel by a different process. All internal channels were finished by AFM. Surface integrity features, such as surface roughness, residual stress, and surface topographies, on the channel surfaces before and after AFM were investigated.

- After AFM for 20 cycles, significant reduction in surface roughness (R_a value) was observed in all three different types of channel surfaces. The high peaks and valleys on all surfaces were almost removed by abrasive grains during AFM.
- Compressive residual stresses were observed in both SLM built and EDM generated channel surfaces after AFM. Plastic flows under the abrasive grains during AFM can be responsible for compressive residual stress generation on the AFM finished surfaces.

- Irregular patterns, such as local wavings, un-melted powders, on both horizontally and vertically SLM built surfaces were completely removed. Remaining molten metals formed on the EDM channels were completely removed by AFM.
- Geometrical deviation from the cylindrical form was observed in the horizontally SLM built surface due to the staircase effect during SLM. Its geometrical error still remains after AFM although its surface roughness was significantly reduced.

Significant surface roughness improvement and compressive residual stresses were observed in all three types of internal channel surfaces after AFM. Thus, the AFM process can make positive effects on the surface integrity on the horizontally and vertically SLM built and EDM generated channel surfaces.

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