Effect of Internal Surface Finishing using Hydrodynamic Cavitation Abrasive Finishing (HCAF) Process on the Mechanical Properties of Additively Manufactured Components

Arun Prasanth. Nagalingam, Vigneshraj. Chinnaiyan Thiruchelvam, Hemanth Kumar. Yuvaraj, Zhi Chao. Yeo, David Wusheng. Toh, Swee Hock. Yeo

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.

Rolls-Royce@NTU Corporate Lab, N3.1-B2a-01, 50 Nanyang Avenue, Singapore 639798, Singapore.

Abstract

Internal channels manufactured using additive manufacturing (AM) techniques are difficult-to-finish due to the presence of several types of irregularities such as loosely attached particles, partially melted particles and semi-welded structures. These irregularities give rise to random roughness distribution across the surface of an AM component. In this study, a novel Hydrodynamic Cavitation Abrasive Finishing (HCAF) process is designed and developed to produce a uniform surface finish throughout the internal surface of an AM component. Internal channels are built from Direct Metal Laser Sintering (DMLS) technique using AlSi10Mg alloy powders. Internal channels with square cross-sectional geometry is built and post-process surface finished using HCAF process. Scanning Electron Microscope (SEM) images of the internal surfaces after finishing showed that most of the material removal is due to hydrodynamic cavitation erosion. The abrasive media added into the cavitating flow aided in material removal as well as improved the surface finish quality. Laser point interferometer roughness measurements showed that the profile surface roughness (Ra) was reduced up to 0.5 µm from the range of 17-19 µm. Furthermore, the improvements in material properties such as hardness and coefficient of friction in an as-built AM surface and after surface finishing using HCAF process are investigated and discussed in detail.

1 Introduction

Additive manufacturing (AM) offers the flexibility to manufacture intricate geometries by transforming complex designs into reality through simple steps. Even though AM offers a wide range of advantages, the as-built surface quality of metal AM components remains undesirable (Average roughness *Ra* in the range of: 5 - 45 µm) [1, 2]. Direct use of AM components without post processing is reported to have a poor life as a result of fatigue failure due to the presence of surface irregularities [3].

Common surface irregularities present in an as-built AM component that gives rise to larger surface roughness values are loosely attached particles [4], partially melted powders [5], semi-welded structures [6], staircasing effect [7], liquid metal splashes and surface cracks [8]. Therefore, as-built AM components must be subjected to post-processing surface finishing before they could be employed for functional performance.

Several post processing techniques are employed on AM components to reduce the as-built surface roughness [9, 10]. Techniques such as laser processing [11] and electrochemical finishing [12] have resulted in achieving promising surface roughness. However, these techniques cannot be used for internal surface finishing due to high laser reflectivity and requirement of the minimum distance between electrodes respectively. Abrasive Flow Machining (AFM) and its variants are used for fine finishing internal surfaces [13]. Surface finish up to few nanometers is achieved using abrasive based technique [14]. However, it is important to note that the initial surface roughness of conventional components is uniform throughout and is around the range of 2.5-5 µm (Ra) before subjecting it to AFM. It is reported that AFM may not be suitable for components with large roughness (Ra: 5 – 45 µm in as-built AM components). Other limitations such as low material removal rate [15] and abrasive agglomeration makes them unsuitable for processing AM components with high and random surface roughness values.

Cavitation is widely used as a constructive tool in ultrasonic machining [16], cavitation drilling [17], cavitation peening for enhancing machining properties [18]. Alternatively, many studies have currently focused to use cavitation effects as a potential tool for surface enhancement (e.g. Surface roughness). Ultrasonic cavitation abrasive finishing (UCAF) process has shown that cavitation has the potential to alter the surface roughness of as-built additive manufactured components [19]. Studies showed that hydrodynamic cavitation can be used as a surface finishing tool in ultrasonic lapping and ultrasonic cavitation finishing [20]. In the past, using hydrodynamic cavitation abrasive finishing (HCAF) process, it was proved that controlled cavitation erosion with abrasives particles at suction pressure conditions can be used for surface finishing the additively manufactured internal channels [21]. The material removal mechanisms in HCAF process were found to be cavitation erosion and abrasive microploughing. However, the effects of using high pumping pressures and changes in material properties after processing was not explored.

Therefore, in this work, effort is taken to investigate the effect of internal surface finishing using HCAF process on the material properties such as hardness and friction coefficient. Surface improvements of DMLS built internal channels will be demonstrated using a newly developed prototype test rig. The improvement in surface roughness (Ra) and material properties such as hardness and wear due to surface finishing using the HCAF process are investigated.

2 Experimentation

2.1 Experimental apparatus

The apparatus used for surface finishing the internal channels of AM components is shown in Figure 1. A pump (50 Hz, 360 lpm, 2900 rpm) is used to pressurize the working fluid and drive it inside the HCAF chamber. The apparatus consists of a partitioned tank to hold abrasive slurry and tap water. The HCAF chamber consists of a cavitation generator (circular orifice) to generate micro hydrodynamic cavitation bubbles. The workpiece to be surface finished is placed behind the cavitation generator using appropriate fixtures. The cavitation bubbles start to implode upon impact with the solid surface and erode the surface material. Silicon carbide abrasive particles (10 µm in size) are added at predetermined concentrations in the tank and used for surface finishing along with cavitation. As the abrasive slurry is driven through the cavitation chamber, the abrasive particles abrade the internal surfaces of the workpiece and produce a smooth surface. The apparatus consists of appropriate control equipment such as heating coils to control the temperature, upstream and downstream pressure control valves to control the pressure inside the HCAF chamber. In addition, the apparatus consists of flow meters, pressure gauges and thermocouples to monitor the process conditions.

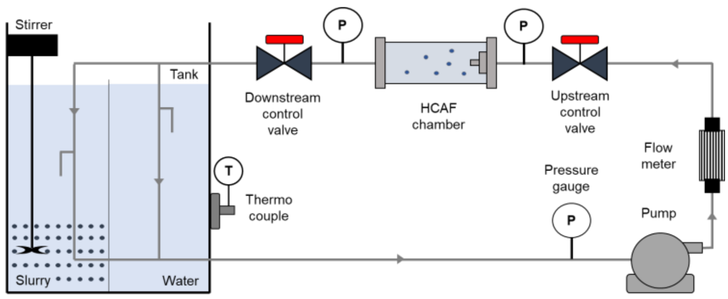


Figure 1: Hydrodynamic cavitation abrasive finishing test setup.

2.2 Experiment methodology

The specimens to be surface finished are built using DMLS technique (EOS, Germany). The work material is selected to be AlSi10Mg alloy. The build orientation of the specimens was kept at 90 degrees. Power size of 25 µm was used for building the components. Internal channels with a square cross-section (sides – 5 mm and wall thickness – 2 mm) were used for this study. The investigations were carried out at varying abrasive concentrations (% weight concentration) (A_c) as listed in Table 1. The process time was fixed at 3 hours as no substantial change in the surface roughness was observed thereafter.

Table 1: Process conditions

Abrasive Concentration (%)	Velocity (m/s)	Upstream pressure (kPa)	Downstream pressure (kPa)	Orifice constriction ratio
0	24.5	400	100	1:5
0.5	24.5	400	100	1:5
1.0	24.5	400	100	1:5
1.5	24.5	400	100	1:5

2.3 Measurements

To assess the potential of HCAF process, the surface morphology of the specimens was observed before and after processing using SEM (JSM5600LV, JEOL, Japan). Profile surface roughness (Ra) were measured using a cut-off of 2.5 mm with evaluation length 12.5 mm as per ISO 4288 using a laser point interferometer (Talyscan 150, Taylor-Hobson, United Kingdom). Roughness measurements were taken at ten random locations throughout the workpiece before and after processing. To identify the material removal rate, mass loss (Δm) measurements were taken before and after processing using a precision mass balance (AX324, OHAUS Corporation, USA). Further, to identify the changes in material properties due to HCAF process, hardness and surface wear of the specimens were investigated. Hardness measurements were taken on the sub-surface perpendicular to the finishing direction using a Vickers hardness tester (FM-300e, Future-tech Corp, Japan). Ten repeated indentations were made for hardness at every 50 µm depth till 200 µm beneath the surface and the results are discussed. To identify the changes in friction coefficient, wear tests were performed using a tribometer (THT high temperature tribometer, CSM instruments, USA) on as-built AM surface and after HCAF processing. The resulting friction coefficient before and after processing are analysed and discussed.

3 Results

3.1 Effect of abrasive concentration

3.1.1. Surface roughness

The effect of abrasive concentration in surface finishing is shown in Figure 2. The initial profile surface roughness (Ra) of as-built AM components varied from ~12 to 20 µm. An excellent surface finishing of 0.82 µm was achieved while experimenting at 0% abrasive concentration. This shows that the material removal is purely due to cavitation erosion (since no abrasives in the flow). Loosely attached and partially melted particles from the surface were removed. However, semi-welded structures were found to deform and were not completely removed. As abrasives particles were added into the cavitating flow, further reduction in surface roughness up to 0.5 µm was achieved at 0.5% and 1.0% abrasive concentrations. Semi-welded structures in the specimen were removed by the abrasive particles present in the cavitating flow. Further increase in abrasive concentration led to an increase in roughness values to 0.66 µm. This is mainly due to excessive abrasive pitting by hard SiC abrasives on the soft aluminium surface.

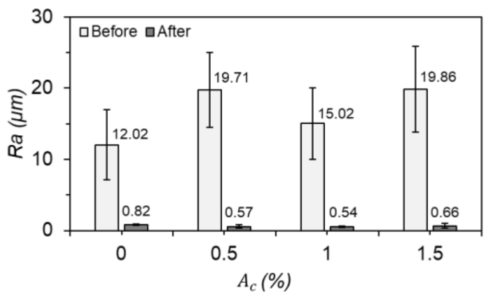


Figure 2: Effect of abrasive concentration in profile surface roughness.

3.1.2 Material removal

The effect of abrasive concentration in material removal is shown in and Figure 3. The material removal at 0% abrasive concentration is 12.37 mg. This confirms that there is material removal due to cavitation erosion. Apart from cavitation erosion, the removal of loosely attached particles present in the specimen surface would have also contributed to the mass loss. As abrasive concentration is increased up to 1.0%, the material removal increases. Further increase in abrasive concentration up to 1.5% has resulted in a reduction in material removal. This might be due to the reason that excessive addition of abrasive concentration will alter the fluid properties (density and viscosity) and cavitation erosion may decrease. Therefore, abrasive concentration up to 1.0% is found to effectively remove material as both cavitation erosion and abrasion mechanisms are involved.

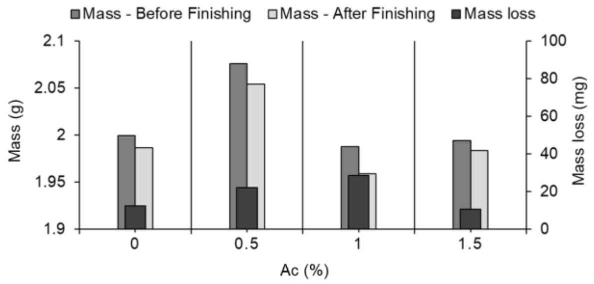


Figure 3: Effect of abrasive concentration in material removal

3.2 Effect of HCAF process on material properties

3.2.1 Hardness

To further evaluate the effects of internal surface finishing on the mechanical properties of AM components, Vickers hardness tests were performed in the specimens. The hardness of as-built AM surface and after the HCAF process are shown in Figure 4. The hardness for 0% abrasives has significantly increased. This is mainly because of the removal of unmelted and partially melted particles from the surface. A maximum of 14% increase in hardness was observed at cavitation finishing condition (0% abrasive concentration). After the addition of abrasive particles, for 0.5, 1.0 and 1.5% abrasive concentration, the hardness values did not increase significantly as compared to 0% abrasive concentration. This is because after the addition of abrasives, cavitation effect will start to diminish and there will be less micro-jet impact on the surface leading to lesser residual stresses. Therefore, hardness increases due to removal of loose and partially melted powders in cavitation finishing conditions and declines with an increase in abrasive concentration.

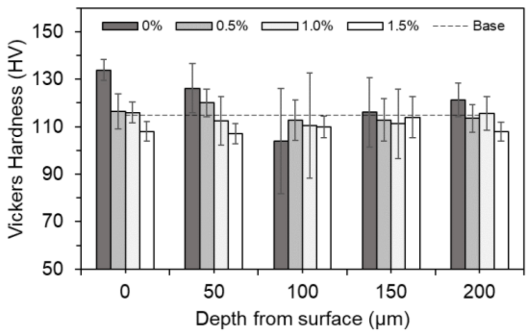
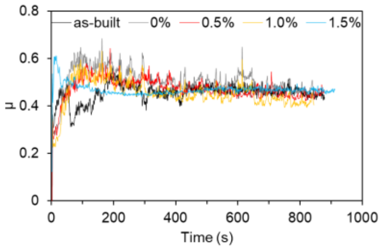
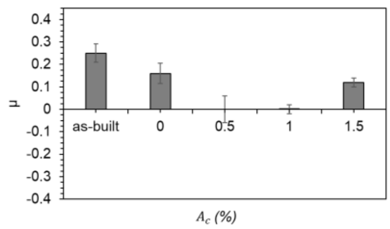


Figure 4: Vickers Hardness after HCAF process

3.2.2 Friction coefficient

The changes in friction coefficient (μ) are shown in Figure 5. The variation in friction coefficient throughout the wear test is shown in Figure 5a. The variation in friction coefficient is only in the first few seconds. The friction coefficient varies at the beginning for each test condition and then reaches a constant at the end of the experiments. This is because the variation in the surface roughness will be effective only for the first few seconds and after that, the top surface will be worn off. In Figure 5b the friction coefficient of the as-built AM surface at the starting is high due to the presence of various irregularities. After surface finishing, the irregularities present in the surface are removed and the surface has become smooth. The smooth surface generated has resulted in a reduction in the friction coefficient of the surface. Therefore, internal surface finish generated by the HCAF process has resulted in a reduction in the surface finish due to the removal of surface irregularities. However, more thorough investigations are needed to reduce the standard deviations and explain the variation in the friction coefficient present at the initial stages of the experiment.





(a) (b)

Figure 5: The friction coefficient of the specimens (a) throughout the test and (b) first 50 seconds.

4 Discussion

The surface morphology of the specimen surface after the HCAF process is shown in Figure 6. Surface finishing at cavitation conditions (0% abrasives) led to the removal of irregularities such as loosely attached and partially melted particles as shown in Figure 6a and b. The material removal during 0% abrasive concentration is purely due to cavitation erosion. The evidence can be observed in Figure 6b from the cavitation pits in the surface. Micro-jet impact due to cavitation implosion resulted in micro-pits on the surface. Repeated micro-jet impact on the surface removes surface material (surface irregularities in this case). After the addition of abrasive particles, even larger sized irregularities were removed due to cavitation erosion as well as abrasion. Due to high pumping pressures (400 kPa), the abrasive velocity at the throat section will be high resulting in high-velocity micro-cutting of surface material. Hence due to the abrasion mechanism, a smooth surface as shown in Figure 6d is achieved. The pits observed might be from the surface pores arising during the manufacturing process or due to cavitation implosion.

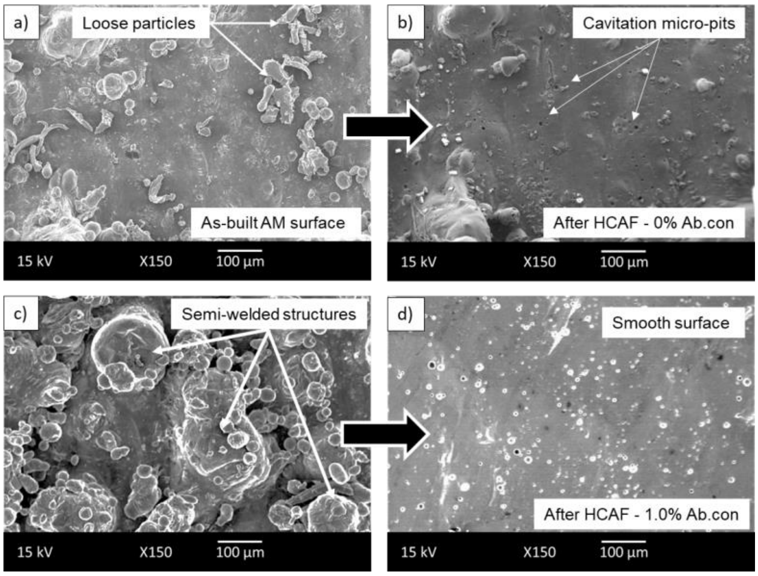


Figure 6: Surface morphology of AM specimens before and after HCAF processing.

Significant changes are observed in the material properties after the internal surface finishing using the HCAF process. The increase in hardness values is due to the residual stresses induced through cavitation implosion. Repeated high-velocity impacts create large compressive stresses on the surface. These compressive stresses resist the force acting on the surface. Therefore, the surface offers higher resistance to indentation while applying loads during hardness tests. The smooth surface has also led to a reduction in friction coefficient (due to the removal of surface irregularities). Therefore, there will be less resistance for the fluid flowing through the internal channels of AM component after surface finishing using the HCAF process.

5 Conclusion

Internal surface finishing using a novel hydrodynamic cavitation abrasive finishing process (HCAF) is explored. In addition, the effect of internal surface finishing on the material properties such as hardness and friction coefficient are investigated. Following are the major conclusions from this study

1) Profile surface roughness (Ra) values from 17-19 µm were reduced until 0.5 µm. Cavitation erosion reduced most of the surface irregularities such as loose

particles and partial melts. Addition of abrasives in the cavitating flow removed larger sized semi-welded irregularities and resulted in a smooth surface finish.

2) After surface finishing, hardness in the internal surface perpendicular to the finishing direction was increased up to 14% due to removal of unmelted and partially melted particles from repeated cavitation implosion on the surface.

3) The friction coefficient of the surface was reduced after surface finishing due to the removal of surface irregularities. However, the friction coefficient reaches a constant after the surface finished layer is removed at the end of the experiments.

Therefore, the HCAF process has resulted in an improvement in the surface finish, improved surface hardness of the specimen providing resistance to external loads and reduced friction coefficient favouring fluid flow in the internal channels of AM components.

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