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Controlled hydrodynamic cavitation erosion with abrasive particles for internal surface modification of additive manufactured components

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Abstract

The understanding and control of wear process can result in advances in manufacturing science. For example, Surface finishing the internal surfaces of a component built using Additive Manufacturing (AM) technique that consists of random roughness distribution throughout its surface is a key problem. This paper describes an innovative approach of using hydrodynamic flow at its cavitating conditions along with freely suspended abrasive particles for finishing the internal surfaces of additive manufactured components. Experiments are conducted on cylindrical as-built aluminium alloy AlSi10Mg parts manufactured using Direct Metal Laser Sintering (DMLS) technique. Application of controlled cavitation erosion by fluids containing entrained SiC particles resulted in a 40% reduction in the average surface roughness (Sa) on the internal surface of a cylindrical specimen. Scanning electron microscope (SEM) observations showed erosion due to hydrodynamic cavitation removed most of the surface irregularities such as loosely attached and/or partially melted powders. Furthermore, direct abrasion after the addition of micro-abrasive media into the cavitating flow deformed as well as partially removed the larger-sized irregularities and resulted in smoother surfaces.

1. Introduction

Surface finishing is an important post-processing step in manufacturing. Surface finishing techniques are used to alter the surface parameters according to functional requirements. Each and every surface finishing technique is capable of producing a unique surface texture. Surface finishing techniques are optimised to achieve the desired surface waviness (long wavelengths) and roughness (short wavelengths) [1]. The surface texture of a component is a crucial factor that controls the friction and transfer layer formation during sliding and movement of any object upon it [2]. Almost in all the cases, a fine surface finish (lower roughness value) is desired. Lower the surface roughness meaning lower the shorter spaced irregularities in the surface. Lesser the irregularities present in the surface better is the functional performance [3].

The internal surface finish quality of a component is critical in mechanical and aerospace industries. Components such as fuel injectors and cooling channels in aerospace industries, exhaust manifolds and fuel transfer lines in automobile industries require a fine surface finish quality (from micro-meters up to few nano-meters). To achieve the desired surface finish quality material has to be removed from the surface in very small quantities at a controlled rate. Abrasive based processes are widely used as internal surface finishing techniques [4]. Abrasive media present in the working fluid flows through the internal surfaces of the component and erodes the surface. Erosion occurs due to the interaction of hard abrasive media with the soft workpiece [5]. Material removal mechanism varies depending on the method of using abrasive particles. Abrasive based processes can be differentiated into two categories based on the method of using abrasives namely 1) Bonded abrasives process [6] and 2) Loose abrasive

process [7]. Loose abrasive methods perform better in finishing the internal surfaces of a component. An example of loose abrasive technique is Abrasive Flow Machining (AFM). AFM technique is used for fine finishing internal surfaces (up to few nano-meters) as it removes fine scale material from the surface at a controlled rate [8]. However, it is reported that low material removal rate in AFM makes it unsuitable for components that have higher surface roughness as large stocks of material have to be removed from the surface to produce the desired finishing effect [9, 10]. Alternatively, free abrasive techniques include abrasive water-based finishing for large scale material removal. However only a coarse surface finish quality is achieved [11, 12].

Industries are now more focused towards Additive manufacturing (AM) as it enables one's flexibility to manufacture any intricate geometry by transforming a design into reality through simple steps. The Powder Bed Fusion (PBF) process is widely adopted to build metallic components with complex geometries such as scaffolds, micro-channels, thin walled protrusions for structural and fluid flow applications to enhance the functional performance of the components. Even though AM offers a wide range of advantages, the as-built surface quality of PBF components remains undesirable (Average roughness Ra in the range of: 5 - 45 μm) at different build strategies [13, 14]. Common surface irregularities present in an as-built AM component that gives rise to larger surface roughness values are loosely attached particles [15], partially melted powders [16], semi-welded structures [17], staircasing effect [18], liquid metal splashes and surface cracks [19]. These surface irregularities mostly affect the fatigue life of the component. It is reported that the surface defects on as-built AM components act as crack initiation sites, resulting in lower fatigue limit [20, 21]. It is also reported that components built using PBF technique exhibit 40% lower fatigue strength compared to wrought and polished components [22]. Applying AFM on complex thin-walled internal channels produced from AM that have higher surface roughness values might take long processing hours (due to the removal of large stocks of material). It may also lead to abrasive agglomeration in complex bends and damage the thin walls of the channel while pumping the working fluid at high pressures (up to 220 bar) [23]. Irregular surface finishing on the edges of a square cross-sectional channel and uneven surface finishing on complex bends are key problems. To solve these problems, initially large stocks of material must be removed followed by fine finishing. To remove large stocks of material, abrasive water jet methods can be used; however, surface quality should be compromised. These are the current limitations of internal finishing techniques to surface finish components built using AM techniques. Due to this limitation, industries are facing difficulties to employ AM components for direct application [24]. Currently, mechanical and aerospace industries are highly interested to explore new potential surface finishing techniques that can remove large stocks of material at the same time producing the desired surface quality.

A combined process similar to abrasive jet finishing to erode the internal surface and a process similar to AFM is required to produce a fine finishing effect. One of the major erosion category identified in fluids is cavitation. Cavitation is said to occur in a hydrodynamic flow as the hydrostatic pressure of the flowing fluid reaches the vapor pressure at a given temperature [25]. Cavitation erosion occurs in materials due to repeated impact of micro-jets generated during cavitation bubble collapse. Cavitation bubble collapse close to solid surface generates local high-velocity micro jets travelling at speeds of 200-700 m/s [26]. These high-velocity microjets strike the solid surface and create micro-pits. The repeated implosion of

cavitation bubbles removes material from a solid surface. Recently, cavitation phenomenon at a controlled intensity is proposed as a surface modification technique for external surfaces [27, 28]. Abrasive media is also used in the cavitating flow to enhance the material removal rate. The presence of abrasives is understood to act as self-nucleating sites. Self-nucleating sites give rise to cavitation bubble growth and increase the process intensity [29, 30]. However, most of the cavitation studies are employed on the smooth external surface and their erosion/damage mechanism is investigated [31, 32]. Till date, up to the author's knowledge, no prior work has been reported by using hydrodynamic cavitation as an internal surface modification technique.

In this paper, hydrodynamic flow at its cavitating conditions along with free abrasives is explored to use it as a possible surface modification technique. [Surface improvements of the internal channels built using DMLS process under PBF category will be demonstrated using a newly developed experimental apparatus.](#) Since micro-abrasive particles are also added to the cavitating flow, the process will be termed as Hydrodynamic Cavitation Abrasive Finishing (HCAF). Improvements in the surface will be discussed using qualitative as well as quantitative results obtained from Scanning Electron Microscope (SEM) images and surface profilometer roughness values respectively.

2. Machine, Method and Measurements

2.1. Design and development of HCAF test setup

To investigate the effects of the proposed technique a closed loop hydrodynamic system as shown in Figure 1 has been designed and developed. The HCAF test setup is developed by keeping in view that it can achieve the necessary fundamental process mechanisms and fulfil all the functional requirements. The apparatus consists of a pump (50 Hz, 2900 rpm, 360 lpm) to drive the fluid from the tank along the circuit. The tank consists of internal partitions in such a way that it can hold tap water in one partition and premixed abrasive slurry in other partition. The pump can drive the fluid from any required partition. In HCAF process, the working fluid is driven through a cavitation generator to generate hydrodynamic cavitation bubbles in the cavitation chamber. The cavitation chamber consists of upstream and downstream pressure regulators to control the cavitation conditions. The apparatus also consists of pressure gauges with an accuracy of $\pm 1\%$ Full Scale (FS) and a magnetic flow meter with an accuracy of $\pm 2\%$ FS deflection at appropriate locations to monitor the flow conditions during experimentation.

Figure 1: Hydrodynamic Cavitation Abrasive Finishing (HCAF) apparatus

During the process the working fluid is driven inside a cavitation chamber with dimensions as shown in Figure 2. The cavitation chamber consists of a cavitation generator (in this case orifice of diameter: 5 mm and thickness: 3 mm) at its upstream position. The cavitation generator is designed such that as the fluid is driven across it, due to the change in flow area the hydrostatic pressure of the fluid reaches the vapor pressure and cavitation bubbles start to nucleate from it and travel inside the test chamber. The cavitation chamber also contains fixtures to accommodate the workpieces. The micro-cavitation bubbles generated flow through the workpiece and implode near the solid surface thus eroding material from the workpiece surface.

Figure 2: Detailed view of the cavitation chamber

2.2. Methodology

2.2.1 Experiments

To identify the potential effects of the HCAF process, experiments were conducted at cavitation conditions with and without abrasive particles for 5 hours. Table 1 shows the experiments performed by varying the abrasive concentration and the magnitude of process variables recorded during the study.

Table 1: Experiment plan

Experiment No.	Velocity (v)	Absolute downstream pressure (P_d)	Abrasive concentration	Cavitation number (σ)
Units	(m/s)	(kPa)	(wt %)	
1	34	13.325	0	0.0065
2	34	13.325	1	0.0065
3	34	13.325	5	0.0065
4	34	13.325	10	0.0065

The cavitation intensity inside the cavitation chamber is calculated by Equation 1 using absolute downstream pressure (P_d), vapor pressure of working fluid at 45°C (P_v), density of working fluid (ρ) and velocity of the fluid flow (v). Intensity of cavitation generated is represented by cavitation number (σ). To determine the effect of abrasives, experiments are conducted with abrasive concentration varying from 0-10% to the total weight of operating fluid. Hard-cut silicon carbide abrasives with a mean diameter of 10 μm and size distribution D50 is used in the study. As the apparatus does not include a temperature controller, experiments were conducted with a 50% duty cycle to prevent temperature rise. A 50% duty cycle ensured that the temperature fluctuations are limited within 5°C.

$$\sigma = \frac{P_d - P_v(T)}{\frac{1}{2}\rho v^2} \quad (1)$$

2.2.2 Workpiece

The workpiece material used in this study is aluminium alloy AlSi10Mg built using DMLS (EOS, Germany) technique. The chemical composition of the powders used is outlined in Table 2.

Table 2: Alloy composition

Element	Sn	Pb	Cu	Ni	Mn	Zn	Ti	Fe	Mg	Si	Al
Mass (%)	<0.02	<0.02	<0.05	<0.05	<0.10	<0.10	<0.15	<0.25	0.2-0.4	9-11	Balance

The layer thickness used during the AM process is 25 μm . A build orientation of 90 degrees with optimal laser scanning strategies were deployed during the build process. The specimens were removed from the build platform through wire-cut. To maintain the as-built condition in the workpiece surface no further post-processing is carried out. The build orientation and the target surface (internal surface) for finishing are represented in Figure 3. Workpiece of geometric dimensions: internal diameter 5 mm, channel wall thickness 2 mm and length 15 mm was selected for this preliminary study.

Figure 3: DMLS built AlSi10Mg workpiece

2.3 Measurement

To analyse the surface morphology, SEM (JSM5600LV, JEOL, Japan) images were taken before and after processing. To quantify the surface, line roughness measurements were taken using a stylus profilometer (SJ-400, Mitutoyo, Japan). A cut-off of 2.5 mm and an evaluation length of 12.5 mm was used during measurements. AM built components are known to have random roughness distribution throughout them. Hence, five repeated measurements were taken at each of the six different locations in the workpiece as shown in Figure 4. Appropriate angle blocks and instruments were used to rotate and hold the workpiece firmly during measurements. Finally, an average of all the measurements was calculated and used for discussion. In addition to line roughness, 3D roughness topography was measured using a non-contact laser interferometer (Talyscan 150, Taylor-Hobson, United Kingdom). The results obtained from the as-built component and after HCAF process are compared and discussed.

1 - 6: Measurement locations

Figure 4: Measurement locations in the workpiece

3. Results

3.1 Surface morphology

An AM component surface will contain various irregularities depending upon its build orientation. The irregularities identified from the workpieces used are of three types. Firstly, smaller irregularities in the size range of (5-15 μm) were identified as loosely attached particles (Figure 5(a)). Secondly, irregularities in the size range of (15-75 μm) were identified to be partially melted powders (Figure 5(a)). These partially melted powders occur due to partial melting and/or fast scan speeds during AM process. Lastly, larger sized irregularities in the

size range of (75-350 μm) were identified as semi-welded structures (Figure 5(b)). These structures arise due to the balling phenomenon and are found to be partially welded inside the component surface.

Figure 5: Surface irregularities present in an as-built DMLS specimen

After the HCAF process, there was a significant change observed in the workpiece surface for all the experiments conducted. Almost all the loosely attached particles and partially melted powders were removed from the surface and a reduction in surface asperities was observed. Figure 6(a) shows the as-built AM workpiece surface and Figure 6(b) shows the smooth surface achieved after the HCAF process from experiment #4.

Figure 6: (a) Surface irregularities present in as-built DMLS specimen (b) Surface after HCAF process (NOTE: SEM images are taken exactly at the same location before and after processing)

On the other hand, semi-welded structures were challenging to be removed due to their large size range (75-350 μm). A partial amount of the semi-welded structures were removed and some were deformed after increasing the processing time from 3 to 5 hours. Hence, removal of larger sized irregularities is dependent on the processing time. In conclusion, more deformation in the semi-welded structures is noticed as the processing time increases.

3.2 Effect of abrasive concentration

To determine the changes achieved in average roughness, the line roughness parameters Ra and Rz were obtained. Figure 7(a) shows the average roughness results before and after HCAF process. The error bars represent the standard error in the measurements obtained from six distinct locations. Average roughness is calculated for the entire specimen from the roughness values obtained at six different locations. The average line roughness (Ra) of the as-built DMLS specimens varied in the range of 15 to 25 μm . The percentage improvement in Ra values were calculated to assess the effectiveness of the surface finish achieved. The maximum improvement of Ra (32%) was observed in specimen #4 and the least Ra (20%) was observed in specimen #1. This shows that pure cavitation has a significant effect on surface roughness improvement on the AM components and addition of micro-abrasives has maximised its potential. The percentage improvement gradually increases along with abrasive concentration as there will be an increase in the number of abrasives particles contributing to the material removal process. Also, the addition of sharp-edged hard cut micro-abrasives will act as self-nucleation spots in a cavitating flow thereby increasing the cavitation intensity and surface finishing effects. Figure 7(b) shows the average peak-to-valley roughness before and after HCAF. The values denote that there is a significant reduction in the peak to valley distance. A minimum of 15% and a maximum of 28% reduction in Rz value is noted in specimens #2 and #3 respectively. Therefore, it can be clearly said that most of the irregularities (loosely attached/partial melts) that acted as peaks on the surface are removed and a smooth surface is achieved.

Figure 7: Surface roughness (a) Ra - Average roughness (b) Rz - Maximum peak-to-valley roughness

3.3 Change in roughness at specific locations

Figure 8 shows the roughness changes recorded at various locations in the AM workpiece. The roughness values of the as-built surface are found to be random throughout the component and are inherent during the build process. Hence, roughness values recorded at six different locations before processing and the change in roughness at these locations after processing are studied. Average line roughness (Ra) and maximum peak-to-valley roughness (Rz) in the surface has reduced after the experiments. However, in few locations roughness values (Ra and Rz) have reduced substantially and at some locations there is only very little changes noticed. In Figure 8(a) (Experiment-Location: 1-1, 2-2, 3-1, 3-2) locations with initial roughness $Ra > 20 \mu\text{m}$ experienced huge roughness reduction due to removal of large stocks of material (presence of large quantities of surface irregularities) removal while locations (Experiment-Location: 1-2, 3-5) experienced very little changes due to fine scale material

removal (presence of few quantities of surface irregularities). In case of maximum peak-to-valley roughness, locations (Experiment-Location: 3-1, 3-2, 4-1, 4-2) with values $R_z > 150 \mu\text{m}$ experienced substantial reduction. In few locations (Experiment-Location: 2-4, 3-3, 3-4 and 4-2) R_z reduction of more than 50% was recorded due to the removal of larger sized irregularities (semi-welded structures) in the stylus measurement location. However, at some locations increase in R_z (Experiment-Location: 2-1, 2-2) was noticed. This might be due to the presence of abrasive pits on the surface thereby leading to increase in peak to valley distance or no change in R_z value (as standard deviations overlap). The removal of semi-welded structures from these locations were ensured using SEM observations. Therefore, maximum peak-to-valley roughness has reduced significantly after processing due to the removal of semi-welded structures that acted as huge peaks on the as-built surface.

Figure 8: Roughness change at a specific location (a) Average roughness (b) Maximum Peak-to-Valley roughness

3.4 Surface topography

The improvements in the surface are further illustrated by comparing 3D surface topography before and after HCAF process. Surface topography measured is levelled and surface roughness analysis is performed. From the levelled 3D surface topography shown in Figure 9, it can be noticed that most of the irregularities are removed from the workpiece surface and a 40% improvement is achieved in the overall surface in experiment #4.

Figure 9: Surface topography before and after HCAF process

Apart from the surface roughness improvements, waviness changes in the surface was also noticed. A cut-off of 0.25 mm was applied to the levelled 3D topography to filter the wavelengths from the surface. The resulting waviness topography (with wavelengths $< 250\ \mu\text{m}$ removed) is used for analysis. Figure 10 shows the waviness topography changes obtained in the specimen after HCAF processing. The waviness error in the surface is due to the presence of semi-welded structures sizing $> 250\ \mu\text{m}$. Due to abrasion on the surface, the waviness error reduces after HCAF process. Abrasion due to the addition of abrasive media removes/deforms the semi-welded structures in the surface. This ensures that the HCAF process removes large stock material from the surface including larger sized irregularities and reduces even the waviness errors present in the surface.

Figure 10: Surface waviness topography before and after HCAF process

Overall, it can be concluded that HCAF process reduces surface errors such as waviness (longer wavelength errors due to the presence of semi-welded structures) and roughness (shorter wavelength errors due to the presence of loose and partially melted particles). To visualize the surface at larger scales, surface topography for an area of 5 mm*1.5 mm is shown in Figure 11. Figure 11(a) represents the surface of as-built AM component and Figure 11(b) represent the surface achieved (reduction in waviness and roughness errors due to the removal of loose/partially melted powders and semi-welded structures) after HCAF process.

a) $S_a = 62.7 \mu\text{m}$

b) $S_a = 44.1 \mu\text{m}$

Figure 11: Surface topography of (a) as-built DMLS specimen (b) after HCAF process

4. Discussions

4.1 HCAF working principle

The detailed working principle of HCAF process is shown in Figure 12. The pump is switched on to recirculate the working fluid in the hydrodynamic loop. The pump speed and pressure are adjusted to the required conditions. The flow reaches the cavitation generator placed upstream to the cavitation chamber and experiences hydrodynamic phase transformation. Cavitation bubbles start to nucleate from the cavitation generator as there is huge pressure reduction (hydrostatic pressure reaches the vapor pressure). The cavitation bubbles flow through the workpiece placed in the cavitation chamber. Cavitation bubbles implode in the vicinity of the solid surface (inner surface of the workpiece) and generate high velocity micro-jets. Repeated cavitation implosion erodes the material from the workpiece surface. In addition to cavitation, loose abrasive particles are added in the flow to abrade the workpiece surface at a fine scale and achieve a smooth surface. As a result of **controlled wear**

due to cavitation erosion and abrasion, irregularities present in the workpiece are removed and a better surface quality is achieved.

Figure 12: HCAF process working principle

Based on SEM observations, a conceptual representation of the material removal mechanism in HCAF process is proposed. Figure 13(a) shows the surface transformation in the component and Figure 13(b) shows the detailed wear mechanism involved during the surface transformation. The primary wear mechanism that contributes to material removal is of interest in this study. As such, during experiment #1, most of the irregularities such as loosely attached particles and partially melted powders were removed from the surface. Since, there is no abrasive particles in this experiment, the only wear mechanism that aids in material removal during this stage is cavitation erosion (Figure 13(b)-1). As surface cracks and pores are inherent in an AM surface, there is a high possibility that heterogeneous cavitation bubble nucleation and implosion from the defects present in the component have contributed to the material removal process (Figure 13(b)-2). After the removal of loosely attached and partially melted powders, cavitation effect did not appear to dominantly remove larger sized irregularities. In experiments #2 - #4, abrasive particles in varying concentrations (1,5,10 %) are added. Due to cavitation implosion and presence of sharp-edged abrasive particles, larger sized irregularities seemed to partially deform/remove. Nevertheless, these larger sized irregularities could potentially be removed if larger sized abrasives are used during processing. The wear mechanism involved after the addition of abrasive particles was found to be micro-ploughing a category of two-body abrasion (Figure 13(b)-3). Overall, controlled wear due to cavitation aided media abrasion resulted in smoothening the entire internal surface of the workpiece.

Figure 13: Material removal mechanism in HCAF

4.2 Material removal mechanism

4.2.1 Hydrodynamic cavitation erosion

To further understand the role of each individual mechanism, the SEM images obtained intermediate to the finishing process are used. Firstly, material removal due to cavitation implosion in experiment #1 is shown in Figure 14 (corresponding mechanism as seen in Figure 13(b)-1,2). It can be observed that most of the loosely attached/ partially melted powders are removed during the initial processing stages (~5 hrs). These micro-jets generated due to cavitation implosion induced cracks in semi-welded structures. Apart from that material removal was not observed on the surface and no improvements in surface roughness were achieved at pure cavitation flow.

Figure 14: Surface transformation of workpiece #1 before and after 5 hrs of pure cavitation
(NOTE: SEM images are taken exactly at the same location before and after processing)

4.2.2 Direct abrasion

Upon addition of abrasives media, further improvements in surface finishing was noticed. Addition of abrasive media enhanced the material removal in HCAF process by further deforming the surface plastically and partially removing the larger sized irregularities. Figure 15(a) and 15(b), shows the surface transformation during experiments #3 and #4 (increase in abrasive concentration) respectively. During this stage, direct abrasion due to abrasive particles were found to be dominant. Abrasive particles mixed in the cavitating flow abraded the surface through micro-ploughing mechanism. Increase in abrasive concentration led to higher abrasive impacts on the surface. Increase in abrasive impact resulted in the further removal of surface irregularities and homogenized the actual AM surface (corresponding mechanism as seen in Figure 13(b)-3). This further explains the increase in percentage improvement achieved in average roughness (Ra) (Figure 7). Therefore, it can be concluded that hydrodynamic cavitation aided with abrasives could potentially be used as an internal surface modification technique for AM components.

Figure 15: Surface transformation in the workpiece (a) #3 after 5 hrs of HCAF (b) #4 after 5 hrs of HCAF
(NOTE: SEM images are taken exactly at the same location before and after processing)

5. Conclusion

Until now, the [surface wear](#) due to occurrence of cavitation phenomenon and the mechanism involved in it is understood to damage and deteriorate the mechanical components. However, in this study, a novel surface modification technique using hydrodynamic cavitation along with abrasives is developed and investigated. The findings in this study suggest that [controlled surface wear due to cavitation erosion](#) could potentially be used as a constructive tool to modify the specimens with poor surface characteristics and high surface roughness. Cavitation erosion at a controlled intensity is found to remove the surface irregularities present in an AM component. [Furthermore, micro-ploughing due to abrasives after the addition of micro-abrasive media in a cavitating flow resulted in smoothing of the internal surfaces of the specimen.](#) An average surface roughness (Sa) reduction of up to 40% was recorded from the investigation. The major [wear](#) mechanism in HCAF process is found to be hydrodynamic cavitation erosion. [In conclusion, controlled wear due to hydrodynamic cavitation erosion aided with abrasive particles reduces the surface roughness of AM components.](#)

Future work will concentrate on studying the process variables and improving the technique to use it for complex internal channels. [Use of pure water at its cavitating conditions along with free abrasives could eliminate the limitations such as abrasive agglomeration, abrasive impingement and damage to thin wall structures during internal channel finishing.](#) Therefore,

further developments in hydrodynamic cavitation abrasive finishing process could potentially result in achieving fine finishing of complex internal channels produced from AM techniques.

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6. References

- [1] B. Griffiths, 2 - The Manufacturing Process Unit Event, in: B. Griffiths (Ed.) *Manufacturing Surface Technology*, Kogan Page Science, Oxford, 2001, pp. 30-69.
- [2] A.A.G. Bruzzzone, H.L. Costa, P.M. Lonardo, D.A. Lucca, *Advances in engineered surfaces for functional performance*, CIRP Annals - Manufacturing Technology, 57 (2008) 750-769.
- [3] R. Leach, *Characterisation of areal surface texture*, Springer, 2013.
- [4] V.K. Jain, *Abrasive-Based Nano-Finishing Techniques: An Overview*, Machining Science and Technology, 12 (2008) 257-294.
- [5] G.W. Stachowiak, *Wear: materials, mechanisms and practice*, John Wiley & Sons, 2006.
- [6] R. Komanduri, D.A. Lucca, Y. Tani, *Technological Advances in Fine Abrasive Processes*, CIRP Annals, 46 (1997) 545-596.
- [7] F. Hashimoto, H. Yamaguchi, P. Krajnik, K. Wegener, R. Chaudhari, H.-W. Hoffmeister, F. Kuster, *Abrasive fine-finishing technology*, CIRP Annals, 65 (2016) 597-620.
- [8] A.C. Petare, N.K. Jain, *A critical review of past research and advances in abrasive flow finishing process*, The International Journal of Advanced Manufacturing Technology, 97 (2018) 741-782.
- [9] V. Jain, S. Adsul, *Experimental investigations into abrasive flow machining (AFM)*, International Journal of Machine Tools and Manufacture, 40 (2000) 1003-1021.
- [10] K.L. Tan, S.-H. Yeo, C.H. Ong, *Nontraditional finishing processes for internal surfaces and passages: A review*, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, (2016).
- [11] R. Kovacevic, *Surface texture in abrasive waterjet cutting*, Journal of Manufacturing systems, 10 (1991) 32-40.
- [12] T. Furumoto, T. Ueda, T. Amino, A. Hosokawa, *A study of internal face finishing of the cooling channel in injection mold with free abrasive grains*, Journal of Materials Processing Technology, 211 (2011) 1742-1748.
- [13] G. Strano, L. Hao, R.M. Everson, K.E. Evans, *Surface roughness analysis, modelling and prediction in selective laser melting*, Journal of Materials Processing Technology, 213 (2013) 589-597.
- [14] J.C. Fox, S.P. Moylan, B.M. Lane, *Effect of Process Parameters on the Surface Roughness of Overhanging Structures in Laser Powder Bed Fusion Additive Manufacturing*, Procedia CIRP, 45 (2016) 131-134.
- [15] E.O. Olakanmi, *Selective laser sintering/melting (SLS/SLM) of pure Al, Al-Mg, and Al-Si powders: Effect of processing conditions and powder properties*, Journal of Materials Processing Technology, 213 (2013) 1387-1405.
- [16] A. Triantaphyllou, C.L. Giusca, G.D. Macaulay, F. Roerig, M. Hoebel, R.K. Leach, B. Tomita, K.A. Milne, *Surface texture measurement for additive manufacturing*, Surface Topography: Metrology and Properties, 3 (2015).

- [17] N. Mohammadian, S. Turenne, V. Brailovski, Surface finish control of additively-manufactured Inconel 625 components using combined chemical-abrasive flow polishing, *Journal of Materials Processing Technology*, 252 (2018) 728-738.
- [18] E. Yasa, O. Poyraz, E.U. Solakoglu, G. Akbulut, S. Oren, A Study on the Stair Stepping Effect in Direct Metal Laser Sintering of a Nickel-based Superalloy, *Procedia CIRP*, 45 (2016) 175-178.
- [19] D. Gu, D. Dai, W. Chen, H. Chen, Selective Laser Melting Additive Manufacturing of Hard-to-Process Tungsten-Based Alloy Parts With Novel Crystalline Growth Morphology and Enhanced Performance, *Journal of Manufacturing Science and Engineering*, 138 (2016) 081003-081011.
- [20] E. Wycisk, A. Solbach, S. Siddique, D. Herzog, F. Walther, C. Emmelmann, Effects of Defects in Laser Additive Manufactured Ti-6Al-4V on Fatigue Properties, *Physics Procedia*, 56 (2014) 371-378.
- [21] J. Tong, C.R. Bowen, J. Persson, A. Plummer, Mechanical properties of titanium-based Ti-6Al-4V alloys manufactured by powder bed additive manufacture, *Materials Science and Technology*, 33 (2017) 138-148.
- [22] T.M. Mower, M.J. Long, Mechanical behavior of additive manufactured, powder-bed laser-fused materials, *Materials Science and Engineering: A*, 651 (2016) 198-213.
- [23] L. Rhoades, Abrasive flow machining: a case study, *Journal of Materials Processing Technology*, 28 (1991) 107-116.
- [24] E.R. Gordon, A. Shokrani, J.M. Flynn, S. Goguelin, J. Barclay, V. Dhokia, A Surface Modification Decision Tree to Influence Design in Additive Manufacturing, 52 (2016) 423-434.
- [25] C.E. Brennen, *Cavitation and Bubble Dynamics*, Oxford University Press, 1995.
- [26] I. Tzanakis, D.G. Eskin, A. Georgoulas, D.K. Fytanidis, Incubation pit analysis and calculation of the hydrodynamic impact pressure from the implosion of an acoustic cavitation bubble, *Ultrasonics Sonochemistry*, 21 (2014) 866-878.
- [27] E. Hutli, M.S. Nedeljkovic, A. Bonyár, N.A. Radovic, V. Llic, A. Debeljkovic, The ability of using the cavitation phenomenon as a tool to modify the surface characteristics in micro- and in nano-level, *Tribology International*, 101 (2016) 88-97.
- [28] K.L. Tan, S.H. Yeo, Surface modification of additive manufactured components by ultrasonic cavitation abrasive finishing, *Wear*, 378-379 (2017) 90-95.
- [29] F. Chen, H. Wang, Y. Tang, S. Yin, S. Huang, G. Zhang, Novel cavitation fluid jet polishing process based on negative pressure effects, *Ultrasonics Sonochemistry*, 42 (2018) 339-346.
- [30] J.R. Laguna-Camacho, R. Lewis, M. Vite-Torres, J.V. Méndez-Méndez, A study of cavitation erosion on engineering materials, *Wear*, 301 (2013) 467-476.
- [31] E. Hutli, M.S. Nedeljkovic, A. Bonyár, D. Légrády, Experimental study on the influence of geometrical parameters on the cavitation erosion characteristics of high speed submerged jets, *Experimental Thermal and Fluid Science*, 80 (2017) 281-292.
- [32] E. Hutli, M.S. Nedeljkovic, N.A. Radovic, A. Bonyár, The relation between the high speed submerged cavitating jet behaviour and the cavitation erosion process, *International Journal of Multiphase Flow*, 83 (2016) 27-38.