euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Electric discharge assisted post-processing of internal surfaces fabricated using metal additive manufacturing

Jibin Boban[1], Afzaal Ahmed[1]

[1]*Department of Mechanical Engineering, Indian Institute of Technology Palakkad, 678557, Kerala, India*

jibinboban143@gmail.com

Abstract

Metal additive manufacturing (MAM) is a promising technology in the modern industrial era owing to its inherent advantages such as design freedom, minimal material wastage, mass customization and suitability for batch production. However, the surface integrity and dimensional accuracy of additively fabricated holes are not acceptable which in turn demands post-processing. Although laser polishing is widely employed for post-processing MAM components, finishing of internal features such as holes is challenging. Moreover, post-processing methods employing chemicals, abrasives and mechanical sources have its own limitations. In light of this, the present study utilizes electric discharge assisted post-processing for finishing additively fabricated holes. Despite the effective removal of surface irregularities, the surface finish (Ra) got enhanced to nearly 1 µm after post-processing. The holes built in horizontal and vertical orientation exhibited significant difference in roughness. Moreover, the time duration required for finishing holes was strongly dependent on the build orientation. The tool electrode rotation reduces the finishing time for horizontally built hole, however had negligible effect on surface finish improvement. It is worthy to note that the circular hole profile is maintained without any deterioration due to the lower discharge energy ensured in the process. Furthermore, numerical simulations indicated lower pressure drop for finished holes which is a major requirement in cooling applications in industries. Therefore, the proposed method exhibit immense potential to be utilized as a post-processing method for additively manufactured holes.

Keywords: Selective laser melting (SLM), Electrical discharge machining (EDM), Surface, Finishing

1. Introduction

The ever-increasing demand for complex shaped metallic components in industrial applications elevated the growth of metal additive manufacturing (MAM) technology in recent times. The feasibility of design freedom and mass customization establishes the superiority of MAM over conventional fabrication methods. Near net shaped parts/components with internal features like holes, cavities etc. can be realized in MAM fabrication. Requirement of internal features like cooling holes is of utmost importance in various sectors such as aerospace, automotive and mould making industries. However, the MAMed parts/components are always accompanied by poor surface integrity and geometrical inaccuracy. Such challenges become aggravated in case of holes fabricated using MAM [1]. The post-processing variants adopted to overcome aforementioned limitations involve laser, chemical, abrasive and mechanical polishing methods.

Conventional drilling of direct metal laser sintered (DMLS) Ti6Al4V was attempted by Ryzawa et al. to investigate the drillability characteristics [2]. However, the process can lead to burr formation both at the entrance and exit of the hole with higher burrs at the exit. In a later study, finishing of selectively laser melted (SLM) Ti6Al4V holes was conducted with removal of support structure within the hole in parallel [3]. The cutting forces were found to be sensitive to the additional material present in the hole which in turn affected the hole surface quality. In addition, some researchers proved that drilling operations can induce scratch marks, colour changes and debris formation over the hole surface [4, 5]. Moreover, the contact of cutting tool with the workpiece in conventional methods can be detrimental in terms of scratch formation when the material being finished is much harder. Other than conventional methods, Tyagi et al. adopted chemical and electrochemical polishing for finishing the internal surfaces of additive manufactured SS316L components [6]. It was observed that chemopolishing could not contribute to significant reduction in internal surface roughness (~13.88 µm to ~5.22 µm (Sa)). On the other hand, electropolishing yielded better surface quality (Sa= ~2.1 µm) than chemopolishing. However, electropolishing is unable to finish internal surfaces where accessibility of counter electrode is restricted. Similar difficulty in finishing internal surface features using electropolishing was also reported in other studies [7]. Recently, electrochemical mechanical polishing (ECMP) was introduced by researchers for finishing internal holes generated by SLM [8]. The combined effect of mechanical abrasion and electrochemical dissolution in ECMP facilitated the elimination of partially melted powder particles present over the hole surface thereby enhancing the surface finish (Sa) from ~14.15 µm to ~3.88 µm. Nevertheless, the contribution of mechanical effect in the hybrid process was only ~0.5 to ~1.8 %. Established post-processing variants like laser polishing is not recommended for finishing internal surface features like holes owing to the limited accessibility of laser head towards such surfaces. Abrasive flow machining (AFM) is a non-traditional method capable of finishing internal cavities [9]. Somehow, a recent study highlighted that significant reduction in Svk value (depth of valleys) cannot be achieved using AFM owing to the difficulty in reaching deep valleys by abrasive particles [10].

It can be concluded that lean consideration has been given in the domain of finishing/post-processing of internal cavities or features generated by MAM. Although existing post-processing methods can enhance the surface integrity of MAM components, several limitations are associated with these methods while finishing internal surface features. In recent times, Boban et al. proposed a low electric discharge energy polishing method called wire electrical discharge polishing (WEDP) for improving the surface integrity of MAM components [11]. The process contributed to submicron surface finish with enhancement in mechanical properties [12]. However, the effectiveness of electric discharge assisted polishing with low energy has not been investigated for internal surfaces. Electric discharge drilling (EDD) has been proven as a promising technology for producing holes on materials irrespective of their hardness [13]. Hence, the technology is widely used in aerospace, biomedical and automotive industries [14]. With the aid of low energy EDD process, the effectiveness of electric discharge assisted polishing on the surface integrity of holes created by MAM is explored. The experiments were conducted by ensuring low discharge energy between tubular tool electrode and MAM hole surface.

2. Mechanism and methodology

2.1. SLM hole fabrication

Multiple holes of 6 mm diameter were built in AlSi10Mg blocks using laser powder bed fusion (LPBF) equipment (Model: EOS M290) under both vertical and horizontal orientation. The depth of the through holes was fixed to be 15 mm. The laser power and scan speed were chosen to be 370 W and 1500 mm/s respectively during the building process.

2.2. Mechanism of electrical discharge drilling assisted polishing (EDDP)

EDDP involves the removal of surface irregularities present over the hole surface by utilizing small discharge energy. The thermal energy generated by electric spark discharges at the interelectrode gap (between workpiece and tool electrode) facilitates the removal of excess material existing as peaks and valleys along the hole surface. The hole ultimately gains the shape of the rounded tool electrode as in EDD through uniform melting and solidification. The pulse on duration and current values for EDDP is kept minimal to prevent the formation of deep craters over the hole surface. The schematic of EDDP finishing/polishing process is shown in Fig.1.

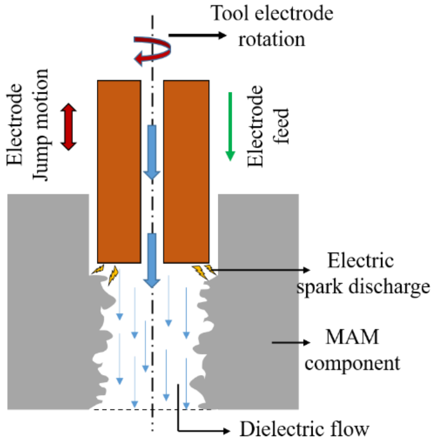

Figure 1. Electric discharge assisted post-processing of MAM holes

2.3. Experimental methodology

AlSi10Mg alloy sample comprising holes was placed in the processing equipment (Model: Mitsubishi die sink EDM EA8S) with the help of suitable fixtures. The diameter of MAMed holes were smaller than intended value of 6 mm due to the presence of excess material over the hole surface. Using 'single edge pickup' option in the controller, co-ordinates were specified in X, Y and Z directions. Subsequently, the 'POLE-P' option available in the system eased the determination of hole centre for finishing. Both pulse on time and peak current setting was kept minimum to maintain minimum discharge energy during the process. Finally, the EDDP process is carried out with an aim to remove the excess material and irregularities present over the rough metallic hole surface. The parameter settings fixed for the experiments is provided in Table 1.

Table 1 Experimental conditions

Experimental parameters	Conditions
LPBF sample	AlSi10Mg
Tool electrode	Copper (Cu)
Tool electrode diameter	6 mm
Dielectric medium	Hydrocarbon oil (DAPHNE CUT HL 25-S)
Peak current (I_P)	2.5 A
Pulse on time (T_{ON})	2 µs
Pulse off time (T_{OFF})	3 µs

3. Results and Discussions

3.1 Surface morphology

The surface morphology of the hole surface was evaluated using an optical microscope (Model: Olympus BX 53). The as-built MAM hole surfaces in both horizontal and vertical build orientations were characterized by the agglomeration of unmelted powder particles as shown in Fig. 2 (a,b). The density of unmelted particles is relatively higher in horizontally built hole owing to the impact of stair stepping effect. After EDDP polishing, the successful elimination of unmelted particles is ensured by the low energy spark erosion induced by the tool electrode. The smooth surface morphology achieved after EDDP is shown in Fig 2 (c,d).

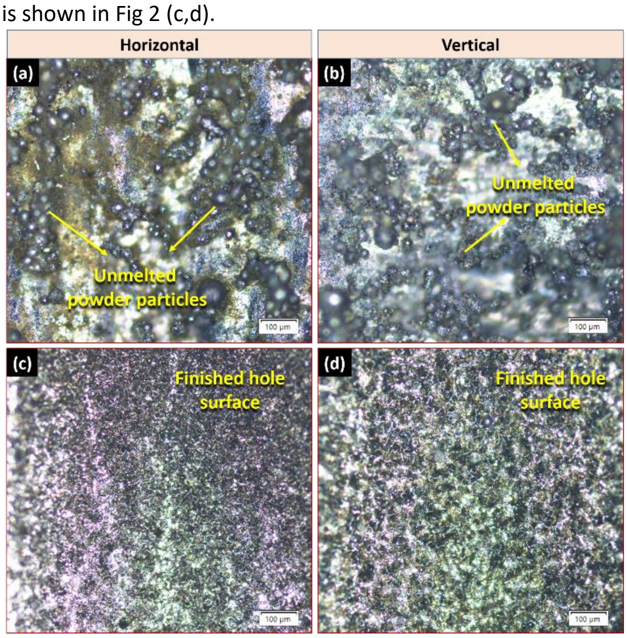

Figure 2. Surface morphology of holes in (a,b) as-built and (c,d) EDDP processed conditions

The topographical images of the hole surface were also captured using optical profilometry (Model: AEP Nanomap 1000 WLI). Significant peaks and deep valleys are evident in case of horizontally built hole (Fig.3 (a)) in comparison with vertically built hole (Fig.3 (b)). However, the uniform melting and solidification ensured during the low energy EDDP process causes the leveling of peaks and valleys to contribute to a smooth surface. From the topographical images, it is clear that the unmelted powder particles are completely removed after EDDP finishing process. The mean diameter of fabricated holes was found to be ~6.12 mm including overcut.

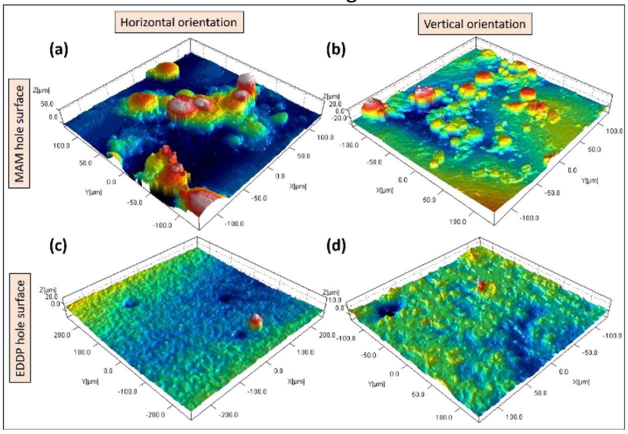

Figure 3. Surface topographical images of hole in (a,c) as-built and (b,d) EDDP processed conditions

3.2 Surface roughness analysis

The roughness values of hole surfaces were evaluated using surface topographical data (Fig.4). The mean roughness (Ra) was evaluated at 5 different regions to confirm the reliability of readings. The horizontally built MAM holes exhibited significantly higher roughness (Ra) of ~15.23 µm (due to stair-casing effect) which is nearly double the roughness of vertically built holes (Ra= ~7.44 µm). The observations corroborate well with the topographical images comprising peaks, valleys and unmleted powder particles. However, drastic improvement in surface finish is achieved by the hole surfaces after EDDP and are nearly same irrespective of the hole build orientation. ~92.8% improvement in surface finish was achieved by the hole built in horizontal orientation (Ra = 1.09 µm), whereas ~86.8% improvement by the vertically built hole (Ra = 0.98 µm).

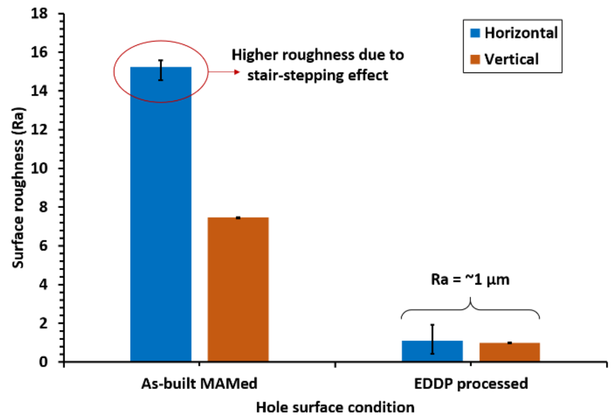

Figure 4. Mean roughness (Ra) of holes in horizontal and vertical build orientations under as-built and EDDP processed conditions

3.3 Effect of tool electrode rotation on surface finish

The effect of tool electrode rotation was investigated to explore its impact on surface finish improvement. The tool electrode was rotated at 30 rpm during EDDP process. The mean roughness (Ra) obtained by the holes with and without rotation is given in Table.2. It can be noticed that the the holes built in both the orientation attain surface finish of nearly 1 µm without any signficant variation in spite of employing tool electrode rotation. Hence, the rotation of tool electrode have negligible impact on improving the surface finish of the hole further.

Table 2 Effect of tool rotation

Conditions	Mean roughness (Ra) after EDDP	
	Horizontal (µm)	Vertical (µm)
Without tool rotation	1.09	0.98
With tool rotation	0.98	1.15

3.4 Effect of build orientation on finishing time

The EDDP time for finishing horizontally and vertically built holes upto a depth of 7.5 mm was inspected. The finishing time was significantly larger in case of horizontal hole as compared to vertical hole (Fig.5). The reason can be attributed to the higher density of irregularities associated with the horizontally built hole. Moreover, horizontal holes are characterized by the presence of excess material due to dross formation at the top surface. Hence, the tool electrode demands relatively more time to remove all such irregularities over horizontal hole surface. Conversely, vertically built holes require lesser finishing time owing to relatively lower density of irregularities.

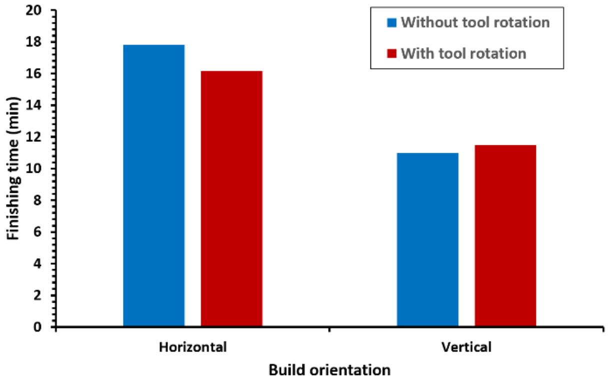

Figure 5. Finishing time for horizontally and vertically built holes

On the other hand, the rotation of tool electrode slightly reduces the finishing duration for horizontal hole. As the excess material/irregularities is not uniform in horizontal hole due to stair stepping effect and dross formation, rotation induces uniform wear of tool electrode and ensures uniform removal of irregularities. However, the surface irregularities are uniformly distributed in vertically built hole which rules out the effect of tool electrode rotation on finishing time. Unlike drilling, only surface irregularities are removed in EDDP thereby suppressing tool wear. Hence, tool rotation does not induce roundness modification and tapering of holes.

3.5 Effect of discharge energy

The circular profile of the hole was observed under lower and higher discharge energy settings. Fig.6 (a) represents the vertically built circular hole profile finished at higher discharge energy settings of T_{ON} = 64 µs and I_P = 10 A. The observations indicate that the circular profile is deteriorated due to material removal in excess at higher discharge energy. Consequently, significant deviation occurs to the 'contouring' path profile and thickness as evident from Fig.6 (a). In contrast, a smooth circular profile is obtained at EDDP settings involving lower discharge energy settings (T_{ON} = 2 µs and I_P = 2.5 A). Moreover, the contour profile around the hole entry is nearly unaffected after EDDP. Minimal discharge energy in EDDP contributes to negligible tool wear and insignificant heat affected zone (HAZ).

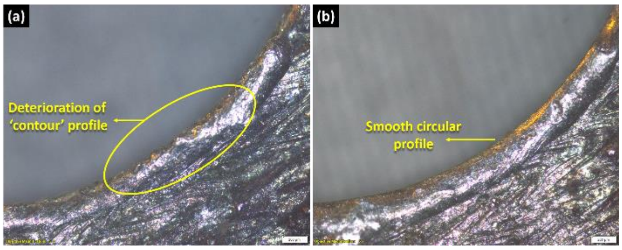

Figure 6. Hole profile at (a) higher and (b) lower discharge energy

3.6 Performance in cooling channels

The performance of as-built MAM and EDDP holes in cooling applications is analysed using a two dimensional fluid flow simulation in ANSYS Fluent 18.2. Steady state simulations were carried out by incorporating k-ω SST turbulence model. The roughness values (Ra) were converted into sand grain roughness (ε) using the empirical relation proposed by Adams et al. [15] as given in equation 1.

$$\varepsilon = 5.863\ Ra \quad (1)$$

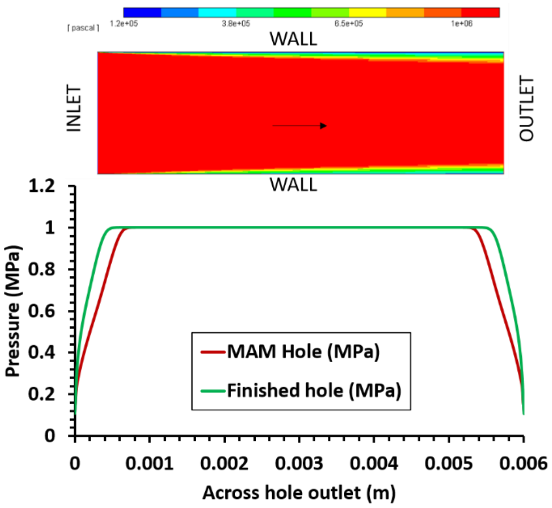

Figure 7. Pressure drop across the outlet for (a) MAM and (b) EDDP finished hole

Comparatively more pressure drop is experienced at the outlet of MAM holes for a length of 20 mm due to the high roughness along the hole walls. However, the better surface finish obtained in case of finished holes reduces the pressure drop (Fig.7) thereby minimizing the requirement of energy to maintain the desired flow. The difference in outlet pressure (facet average) for MAM and finished holes is provided in Table 3.

Table 3 Outlet pressure for MAM and finished holes

Build orientation	Outlet pressure (MPa)	
	MAM Hole	Finished Hole
Horizontal	0.86	0.905
Vertical	0.87	0.906

4. Conclusions

The present study investigated the performance of low energy electric discharge drilling assisted polishing (EDDP) process on enhancing the surface integrity of MAMed holes. The unmelted particles and surface irregularities present over the surface of MAM built holes is very much reduced after EDDP process. Although higher roughness was exhibited by horizontally built holes relative to vertical holes, nearly same surface finish (~1 µm) is achieved through EDDP processing. The effect of tool electrode rotation was found to be negligible in improving the surface finish of hole. However, tool rotation could minimize the finishing speed for horizontally built holes. Vertically built holes require less finishing time on account of reduced density of irregularities. Lower discharge energy settings in EDDP process contributes to a smooth circular profile without deteriorating the hole surface. Furthermore, numerical simulations highlight that the finished holes are effective in minimizing the pressure drop at outlet which forms a demanding requirement in industrial cooling applications. Thus, EDDP can be a promising technology in post-processing MAMed internal holes.

Acknowledgement

The authors are grateful to the staff in Central Instrumentation Facility (CIF) and Central Facility for Materials and Manufacturing (CFMM) at IIT Palakkad for extending their support in characterization and material fabrication.

References

[1] Liu C, Cai Z, Dai Y, Huang N, Xu F, Lao C 2018 Experimental comparison of the flow rate and cooling performance of internal cooling channels fabricated via selective laser melting and conventional drilling process. *Int. J. Adv. Manuf. Technol.* **96** 2757-2767

[2] Rysava Z, Bruschi S, Carmignato S, Medeossi F, Savio E, Zanini F 2016 Micro-drilling and Threading of the Ti6Al4V Titanium Alloy Produced through Additive Manufacturing. *Procedia CIRP* **46** 583-586

[3] Hintze W, Schötz R, Mehnen J, Köttner L, Möller C 2018 Helical milling of bore holes in Ti6Al4V parts produced by selective laser melting with simultaneous support structure removal. *Procedia Manuf.* **18** 89-96

[4] Karabulut Y, Kaynak Y 2020 Drilling process and resulting surface properties of Inconel 718 alloy fabricated by Selective Laser Melting Additive Manufacturing. *Procedia CIRP* **87** 355-359

[5] Ming W, Dang J, An Q, Chen M 2020 Chip formation and hole quality in dry drilling additive manufactured Ti6Al4V. *Materials and Manufacturing Processes* **35** 43-51

[6] Tyagi P, Goulet T, Riso C, Stephenson R, Chuenprateep N, Schlitzer J, Benton C, Garcia-Moreno F 2019 Reducing the roughness of internal surface of an additive manufacturing produced 316 steel component by chempolishing and electropolishing. *Addit. Manuf.* **25** 32-38

[7] Ferchow J, Hofmann U, Meboldt M 2020 Enabling Electropolishing of Complex Selective Laser Melting Structures. *Procedia CIRP* **91** 472-477

[8] Zhao C, Qu N, Tang X 2021 Electrochemical mechanical polishing of internal holes created by selective laser melting. *J. Manuf. Processes* **64** 1544-1562

[9] Tan KL, Yeo S-H, Ong CH 2016 Nontraditional finishing processes for internal surfaces and passages: A review. *Proc. Inst. Mech. Eng., Part B: J. Eng. Manuf.* **231** 2302-2316

[10] Han S, Salvatore F, Rech J, Bajolet J, Courbon J 2020 Effect of abrasive flow machining (AFM) finish of selective laser melting (SLM) internal channels on fatigue performance. *J. Manuf. Processes* **59** 248-257

[11] Boban J, Ahmed A, Rahman MA, Rahman M 2020 Wire electrical discharge polishing of additive manufactured metallic components. *Procedia CIRP* **87** 321-326

[12] Boban J, Ahmed A 2021 Improving the surface integrity and mechanical properties of additive manufactured stainless steel components by wire electrical discharge polishing. *J. Mater. Process. Technol.* **291** 117013

[13] Boban J, Ahmed A, Assam A 2021 Effect of recirculation zone on debris evacuation during EDM deep hole drilling. *Procedia CIRP* **102** 393-398

[14] Ahmed A, Boban J, Rahman M 2021 Novel EDM deep hole drilling strategy using tubular electrode with orifice. *CIRP Ann.* **70** 151-154

[15] Adams T, Grant C, Watson H 2012 A Simple Algorithm to Relate Measured Surface Roughness to Equivalent Sand-grain Roughness. *Int. J. Mech. Eng. Mechatron.* **1** 66-71