Ultra-precision surface treatment of directionally additive manufactured Al-Si alloy

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Additive manufacturing (AM) is a swiftly advancing domain that facilitates the production of intricate and complex parts with desired customization. The technology creates opportunities for batch production with negligible wastage of material. However, the AM parts tend to have poor surface integrity, which adversely affects the functional performance of the component. The presence of surface defects/irregularities like balling defects, spattering, inadequately melted particles, etc. can hinder the acceptability of AM parts in industries. Therefore, post-treatment of AM surfaces is highly important to meet industrial quality standards. The generally adopted post-treatment methods like laser polishing, chemical finishing, abrasive fluidized bed machining, etc. have been proven to contribute sub-micron surface finish on metal AM parts. However, certain applications in space and defense sectors demand extremely smooth surfaces with nano-level finish on components like metallic mirrors, reflective surfaces, solar concentrators etc. Therefore, the present study explores the potential of ultra-precision diamond turning in improving the surface quality of additively manufactured metallic surfaces beyond sub-micron regime. Considering the potential of Aluminum alloys in reflective optics applications, laser powder bed fused AlSi10Mg is considered in the study to assess the ultra-precision machining performance in terms of surface quality and form accuracy. The results from the study showed that the build orientation of directionally printed samples (horizontal and vertical) played a vital role in deciding the post-treatment process performance. After implementing the ultra-precision finishing process, nano-level surface finish was achieved on both horizontally (Ra= ~39.8 nm) and vertically (Ra= ~29.0 nm) printed samples with the latter being smoother. Moreover, micro-cutting experiments confirmed that the vertically built samples experienced distinct forces relative to horizontal samples owing to the microstructural differences with respect to orientation. Further, the study showed that micro-feature generation close to ideal design can be successfully accomplished on additively printed AlSi10Mg samples regardless of the build orientation. Thus, the proposed approach can be useful in elevating the potential of laser powder bed fused AlSi10Mg in metallic optics applications.

NOMENCLATURE

AM = Additive manufacturing
LPBF = Laser powder bed fusion
AFM = Abrasive flow machining
UPDT = Ultra-precision diamond turning

1. Introduction

Additive manufacturing (AM) is a rapidly evolving technology gaining considerable attention in industries due to its inherent design freedom in the production of complex parts. The possibilities of mass customization and batch production opportunities establish the dominance of AM technology over conventional manufacturing techniques. Nevertheless, the poor surface integrity associated with the printed parts restrict the acceptability of AM technology at application level in industries. Therefore, post-processing of metal AM surfaces is inevitable to meet industrial expectations and ensure the successful adoption of fabricated components in desired applications. Till date, researchers have conducted in-depth investigations on established surface treatment variants like laser polishing, abrasive assisted finishing, chemical polishing etc. to assess their potential in improving the quality of metal AM parts. A brief review of such remarkable studies is provided in the upcoming section.

2. State-of-the-art in post-processing of additively manufactured Al-Si alloys

Conventional mechanical surface treatments have proven efficiency in post-processing metallic AM parts. The vibro-finishing strategy explored by Atzeni et al. [1] on LPBF AlSi10Mg samples showed nearly 90% improvement in surface finish relative to as-printed samples. The process contributed successful suppression of roughness peaks and valleys on the surface. However, the process resulted in excess material removal at the sample edges leading to undesirable edge rounding effect. Similarly, another study confirmed that the final finish achieved is highly dependent on the size of the grains used in vibro-finishing [2]. Excess abrasion and inefficient defect removal are the challenges noticed corresponding to larger and coarser grains used in the study.

In addition to mechanical post-treatments, efficacy of abrasive aided polishing methods were also investigated by researchers. Atzeni et al. [3] investigated the abrasive fluidized bed (AFB) finishing method to assess its effectiveness in post-processing AM AlSi10Mg alloys. The process involved placing the substrates in a fluidized bed enriched with abrasive particles. The AFB process notably decreased the surface roughness (Sa) of the as-printed material from ~16.72 μm to ~1.5 μm. The high-speed impact of abrasive particles caused microcutting and microploughing effects leading to effective removal of partially melted particles from the surface. However, the research by El Hassanin et al. [4] on rotation-assisted AFB demonstrated that high hardness ratio between the abrasives and the base material can limit the method's effectiveness in enhancing surface integrity. Similar to AFB, abrasive flow machining (AFM) variant inspected by Peng et al. [5] also offered significant enhancement in surface finish (~13 μm to ~1.8 μm) by successfully eliminating the surface defects such as powder adhesion and balling defects. In addition, AFM induced residual stresses of compressive nature over post-treated AlSi10Mg surface.

Instances of adopting thermal post-treatment methods on metal AM parts can be also observed in the past literature. Electric discharge assisted polishing is also an excellent post-treatment option that can guarantee exceptional geometrical accuracy and sub-micron surface finish on processed components [6]. Nevertheless, the processed surface is characterized by the existence of a re-solidifed oxygen-rich layer. Laser polishing (LP) is another efficient thermal post-treatment method in processing additively printed AlSi10Mg parts. Investigations carried out by Zhou et al. [7] while polishing LPBF AlSi10Mg parts using laser beam reported an improvement in surface finish by ~71.3% from an initial roughness of ~29.3 μm (Sa). Moreover, ~58.4% improvement in surface hardness was reported after LP in the same work.

Considering the need of AM technology in producing complex components, Scherillo [8] explored the competence of polishing using chemicals in enhancing the surface quality of additively manufactured Al-Si alloy parts. Smooth surface was successfully achieved on the samples through chemical machining (CM) followed by chemical brightening (CB) stages. CM concentrated on removing the non-melted powder particle traces, whereas the latter focused on eliminating the residual cracks and pores left on the surface after CM. However, the challenges in process control and unevenness in material removal related to chemical polishing put restrictions in the adoption of the process on a larger scale in industries.

Precise removal of surface imperfections from metal AM parts is crucial for achieving optimal functional performance without compromising material properties. Current state-of-the-art surface post-treatment techniques typically achieve only sub-micron surface finish, and each method experiences significant limitations while processing AM components. In metallic optics applications, the need for defect-free parts with nano-scale surface finishes is paramount. Boban et al. [9] demonstrated that ultra-precision diamond turning (UPDT) offers a viable approach to attain nano-finish on metal AM parts. However, there has been insufficient efforts into investigating the role of build orientation of AM parts in deciding the part machinability at ultra-precision level. Thus, the present study aims to explore the impact of build direction on the ultra-precision machinability and micro-texturing capabilities of LPBF AlSi10Mg samples.

3. Materials and methods

3.1 LPBF printing

With the assistance of a direct metal laser sintering (DMLS) system (Model: EOS M290), cylindrical samples with a circular cross-section were fabricated from AlSi10Mg powder using laser powder bed fusion (LPBF) process. Each sample measured 30 mm in length and 6 mm in diameter. The entire set of samples were printed in vertical and horizontal orientations with end surfaces parallel and perpendicular to build direction respectively. Further, the LPBF process was conducted in an inert argon atmosphere to prevent oxidation. Table 1 presents the specific parameter conditions utilized during the LPBF process.

Table 1 LPBF conditions

AM Parameters	Conditions
Powder particle size (μm)	30 – 70 (Mean size = ~46)
Laser power (W)	370
Layer thickness (μm)	40
Hatch spacing (μm)	130
Scanning speed (mm/s)	1500

3.2 Experimental methodology

The finishing experiments were conducted using using an advanced ultra-precision diamond turning lathe (Model: Optima 100, Mikrotools). The equipment features hydrostatic guideways to ensure precise motion control along each axes (X and Z) and a specialized air-bearing spindle during diamond turning. A polycrystalline diamond (PCD) tool, with a nose radius of ~0.5 mm was employed for the experiments. Using optimal parameters identified from preliminary trials (depth of cut: 2 μm, feed rate: 6 mm/min, spindle speed: 1250 rpm), face-turning was performed on as-printed samples in both vertical and horizontal orientation. The printed samples were finished through multiple passes with the PCD tool until the total depth of cut approached the maximum peak-to-valley height roughness (Sz). The experimental methodology is illustrated in Fig. 2. Further, micro-texturing was carried out on finished samples with the additional support of C axis to evaluate the dimensional accuracy with respect to part build orientation.

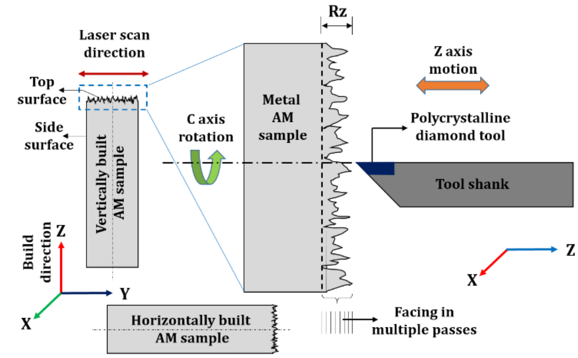

Fig. 1 Experimental methodology for UPDT experiments

4. Results and discussions

4.1 Surface integrity

The surface roughness associated with the as-printed and finished samples were measured using a non-contact type (optical) profilometer (Model: AEP Nanomap 1000 WLI). The arithmetic mean roughness (Sa) for as-printed sample was ~6.32 µm in horizontal orientation (end of surface printed along build direction) and ~5.89 µm in vertical orientation (end surface printed perpendicular to build direction).

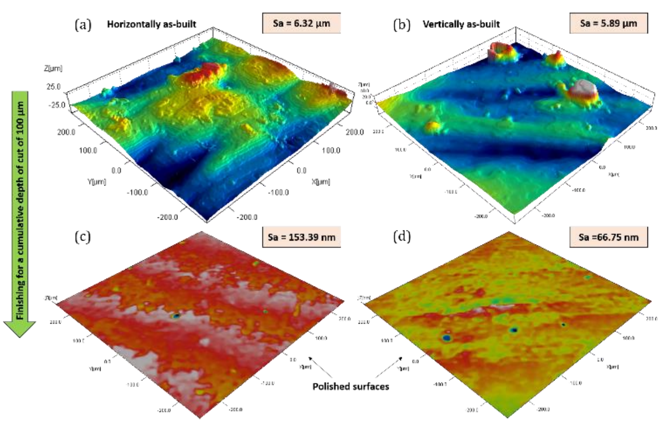

Fig. 2 Surface topography of (a,b) as-printed and (c,d) UPDT surfaces

As compared to the vertically built sample (VBS) end surface, the end surface of horizontally built samples (HBS) exhibits higher roughness owing to the relative abundance of surface irregularities caused by powder particle adherence from surrounding zones during LPBF. The surface roughness was significantly decreased after employing UPDT (upto a total depth of cut equivalent to the peak-to-valley roughness (Sz)) leading to a final finish of ~153.39 nm and ~66.75 nm respectively on the end surfaces of HBS and VBS respectively. Further passes beyond Sz value upto a cumulative depth of cut of 25 µm generated a surface finish of ~39.8 nm and ~29.0 nm respectively on HBS and VBS. The latter features smooth surface finish which can be attributed to the microstructural differences with respect to the build orientation of the samples.

4.2 Microstructural analysis

The microstructure corresponding to the end surfaces of HBS (Fig.3 (a)) and VBS (Fig.3 (b)) was analyzed using a metallurgical microscope (Model: Conation Technologies, Suxma series) after etching the manually polished AM samples using Keller's reagent. Material melt history comprising traces of melt pool generated during LPBF was clearly evident on HBS end surface.

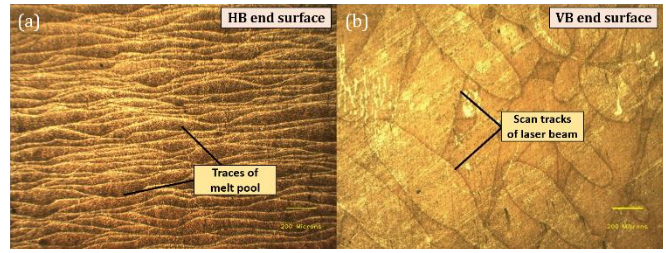

Fig. 3 End surface microstructure related to (a) HBS and (b) VBS

In contrast, VBS samples were characterized by the presence of multiple overlapping laser beam scan tracks with clearly defined edges in a segregated manner. The independent scan track zones are aligned at a distinct angle on account of the optimal 67° layer rotation fixed during printing. Thus, the significant difference in microstructural attributes can impart a crucial role in deciding the machining performance of the samples.

4.3 Machining performance

The machining performance was assessed by executing micro-cutting experiments on the sample end surfaces and measuring the cutting forces in parallel with the assistance of a multi-channel dynamometer (Model: 9119AA2, Kistler). The typical microgrooves produced at a cutting speed of 50 mm/min and 5 µm depth of cut on HBS and VBS are provided in Fig.4 (a) and Fig.4 (b) respectively.

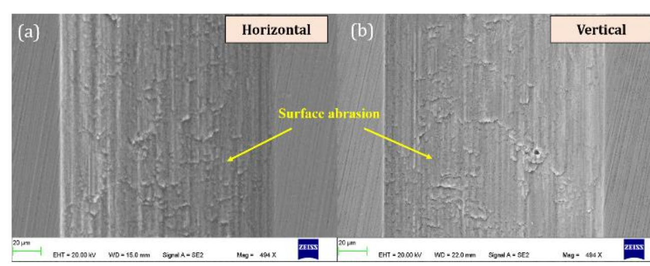

Fig.4 Microgrooves produced by micro-cutting experiments on (a) HBS and (b) VBS

Evidences of surface abrasion can be clearly observed over microgroove on account of the typical microstructure of AlSi10Mg. The underlying reason can be due to the peculiar microstructure of LPBF AlSi10Mg as shown in Fig.5 (a,b). The variation in the deformation behavior exhibited by the regions with harder Si particles (in the form of cellular network (Fig.5 (b)) relative to the softer matrix of Al induces the surface abrasion during UPDT.

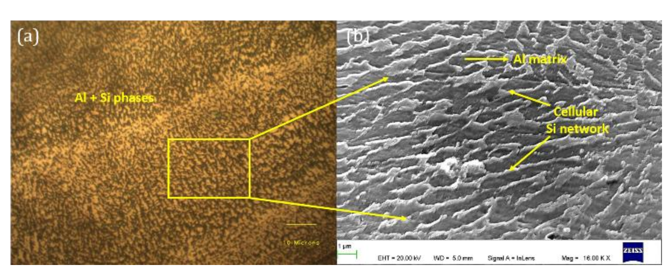

Fig.5 AlSi10Mg microstructure at (a) higher (100X) and (b) ultra-high magnifications (16 KX)

The cutting force generated in micro-cutting of end surfaces with respect to different build orientation is depicted in Fig.6. It is clearly evident that micro-cutting of HBS end surface parallel to build direction shows relatively higher cutting force compared to cutting in the perpendicular direction. As columnar grains will be aligned along the build direction during LPBF process, the yield strength will be higher in the same direction such that cutting in parallel incurs higher force. However, no significant change in cutting forces occur in VBS while cutting along X and Y axis owing to the random orientation of grains at VBS end surface.

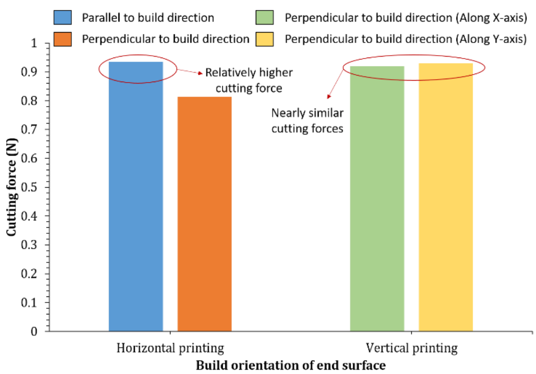

Fig.6 Cutting force magnitude obtained during micro-cutting of HBS and EBS surfaces.

4.3 Micro-texturing efficacy

LPBF AlSi10Mg samples possess a microstructure and properties completely distinct relative to conventional samples. Therefore, the viability of UPDT in accomplishing microtexturing on LPBF samples was inspected by developing a toolpath for a sinusoidal wave (Fig.7 (a,b)) using MATLAB followed by subsequent machining on the samples. The synchronized motion of linear axes (X,Z) and rotational C axis facilitates precise tracing of the designed tool path to ultimately produce the feature. It can be observed from Fig.7 (c,d) that negligible deviation in geometrical profile and dimension is experienced while adopting UPDT for micro-texturing on LPBF AlSi10Mg samples. Thus, the micro-texturing efficacy of UPDT process is nearly independent of the AM process induced material properties although minor deviations occur probably due to LPBF defects and non-homogenous microstructure.

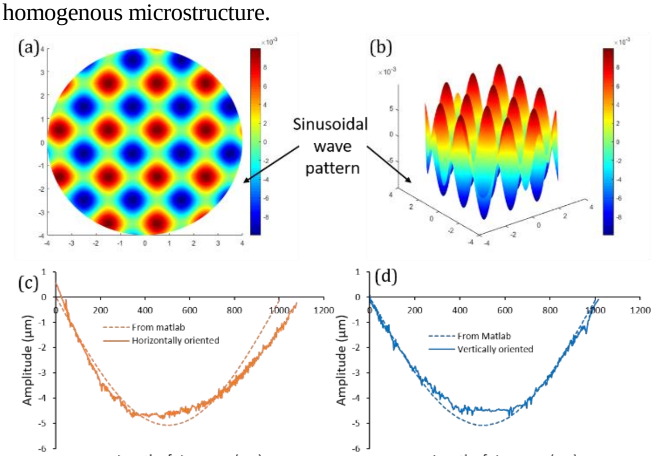

Fig. 7 MATLAB Sinusoidal wave design in (a) 2D, (b) 3D and (c,d) comparison of achieved profile after UPDT with respect to ideal design

4. Conclusions

The present study investigated the influence of build direction on the ultra-precision machinability and micro-texturing capabilities of LPBF AlSi10Mg samples. LPBF AlSi10Mg samples attain exceptional nanofinish through UPDT after a cumulative depth of cut equivalent to areal peak to valley roughness (Sz). The observed microstructural differences related to the end surfaces in horizontal and vertical build orientation affected the ultra-precision machining performance in terms of surface finish and cutting forces. Relatively higher cutting force was experienced while executing micro-cutting on end surface in a direction parallel to the build direction probably due to the increased yield strength in the direction of columnar grain alignment. Regardless of build orientation, the UPDT process ensures micro-feature profile generation on metal AM alloys with negligible deviation in dimensional accuracy. Thus, the process exhibits potential in overcoming the micro-texturing limitations of LPBF technology.

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REFERENCES

1. Atzeni, E., Balestrucci, A., Catalano, A.R., et al.: Performance assessment of a vibro-finishing technology for additively manufactured components. Procedia CIRP 88, 427-432 (2020).
2. Bhaduri, D., Penchev, P., Dimov, S., Essa, K., Carter, L.N., et al.: On the surface integrity of additive manufactured and post-processed AlSi10Mg parts. Procedia CIRP 87, 339-344 (2020).
3. Atzeni, E., Barletta, M., et al.: Abrasive Fluidized Bed (AFB) finishing of AlSi10Mg substrates manufactured by Direct Metal Laser Sintering. Additive Manufacturing 10, 15-23 (2016).
4. El Hassanin, A., et al.: Rotation-assisted Abrasive Fluidised Bed Machining of AlSi10Mg parts made through SLM Technology. Procedia Manufacturing 47, 1043-1049 (2020).
5. Peng, C., Fu, Y., et al.: Study on improvement of surface roughness and induced residual stress for additively manufactured metal parts by abrasive flow machining. Procedia CIRP 71, 386-389 (2018).
6. Boban J, Ahmed A.: Electric discharge aided surface post-treatment of laser powder bed fused non-planar metallic components for enhanced form accuracy. Journal of Manufacturing Processes 109, 564-582 (2024).
7. Zhou, J., et al.: In-Situ Laser Polishing Additive Manufactured AlSi10Mg. Materials 14(2), 393 (2021).
8. Scherillo, F., Manco, E., et al.: Chemical surface finishing of electron beam melted Ti6Al4V using HF-HNO3 solutions. Journal of Manufacturing Processes 60, 400-9 (2020).
9. Boban, J., Deshmukh, S.M., Ahmed, A.: Ultra-precision surface finishing and feature generation on metal additive manufactured components with controlled tool path design. Procedia CIRP 119, 450-455 (2023).