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Towards post-processing as a key process variable in the AM design chain

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Abstract
Additive manufacturing (AM) has significant potential for use within a number of precision based industries such as aerospace, automotive and medical. However, a key barrier to the adoption of this technology is the high surface roughness of as-built AM parts. Current approaches for the post-processing of AM parts often focus on traditional technologies which can struggle with the complex geometries made possible with AM. There is also a lack of process control, which is required for high value manufacturing industries. Expert advice is often only sought after the part has been designed and built, and manual processes are often relied on thus increasing finishing cost and touch-time. Addressing this surface roughness barrier through improved control, simulation and design is therefore crucial to AM development. By modelling the finishing operations more accurately a predictive tool can be developed which can improve down-stream operation time and quality by impacting decisions at the initial design stage. In order to develop a modelling tool for finishing complex AM parts, laser polishing (as a finishing process) will be investigated due to its high repeatability and controllability [1]. Selective laser melted (SLM) Ti6Al4V and In718 parts of varying thicknesses have been laser polished at different hatch, power and velocity parameters to calibrate and validate a predictive modelling tool. Alongside this the framework for a knowledge platform including experimental data for both targeted, automated abrasive finishing and laser polishing will be presented. This will allow a reduced reliance on 'expert knowledge' and for the integrated design process chain for AM post-processing to be shared.

Laser polishing, Ti6Al4V, Additive manufacturing, Modelling, Automated de-burring, Automated abrasive finishing, design tool

1. Introduction

There is a common misconception within the additive manufacturing (AM) field that a useable component is available immediately after the build process has completed; there are many time-consuming (often manual) and costly steps to go through before it is ready. These include post-processing the component itself which requires specific knowledge and techniques [2], especially related to support removal and finishing [3], as well as inspection of the component such as dimensional and defect evaluation. These necessary steps are commonly overlooked [4] and are sometimes described within the AM industry as "AM's dirty secrets" [5], but are often just as critical (if not more critical) to the functionality and the ultimate capability of metal AM processes [6]. In addition, it is common to sub-contract out post-processing steps due to the high capital cost of equipment which leads to a lack of control on the final component due to the multiple steps used and heavy reliance on manual support removal and polishing. As the AM market increases (~20% CAGR Wohlers 2015 [6]), an estimated 25% of new AM parts will be too complex for current automated methods (increase in complexity seen in Innovate UK ALMER Project). To enable designers to exploit the geometric freedom offered by additive manufacturing, build and post-processing strategies must be developed that can handle geometrically complex features that are defect-free.

Laser polishing and mechanical finishing have high potential for finishing fine features generated by additive processes, since they can be applied to targeted areas with large variations in curvature e.g. impellers, ball joints, edge deburring [7].The EU AM SRA report [8] outlines the need for optimised finishing strategies, to address the key challenges of improving surface quality for complex shapes and improving fatigue properties. Temmler et al. [9] used a Crocodile X sensor system to capture surface data, and feed this into a CAD / CAM model to generate the laser tool path and predict surface roughness, however no feedback loop to improve the process was incorporated after the polishing had been completed. Mature physics-based simulations for the interaction of the finishing media with the workpiece are not available for laser polishing and mechanical finishing. However, there is significant development within academia around melt pool dynamics and process modelling for laser polishing [9] and for other finishing process e.g. mass finishing [10] and abrasive flow [11].

Within this paper experimental trials are presented which are used to create an experimental model for laser polishing of SLM parts using surface texture measurements. This is then presented as part of a framework for a knowledge database for post-processing of AM parts.

2. Method

2.1 Laser Polishing Predictive Model

Ti6Al4V plates were produced using a Renishaw AM250 L-PBF machine. 50mm x 50mm square plates were produced with thicknesses of; 2mm, 4mm, 6mm and 8mm.. Similar sized In718 SLM plates were also produced, using an EOS M400 machine. A response surface design of experiments (DOE) approach was used for model calibration and validation. Polishing was done using parameter sets with individual values between 100-450mm/s scan speed, 10 - 50µm hatch and 150 – 350W power were performed. An IPG CW 500W fibre laser was used, which has a wavelength of 1070nm and maximum power output of 500W. The laser beam passed through an IPG scanning head, with a focal spot size of 350µm. The AM components were placed in an argon filled chamber, with a 5l/min argon flow rate to ensure sufficient atmospheric shielding. The experimental set-up is shown in Figure 1. The as-built surface roughness and polished roughness were measured using a focus-variation machine. The areal roughness, S_a, parameter was evaluated to assess the difference between as-built and polished surfaces. All measurements were taken at the filer values according to ISO 4288. The average roughness parameter has been chosen in this case as a metric that is widely used by aerospace and power customers, based on their historical specifications for more traditional manufacturing methods and finishes. Therefore the use of this parameter will allow easy comparison for these applications, especially as the surface roughness is being reduced and AM features removed. For all DOE trials the associated roughness was recorded to create a large database of values at different parameters. This data was then evaluated in Minitab and Matlab to create an initial predictive model for the final S_a based on as-built starting roughness and the laser polishing parameters.

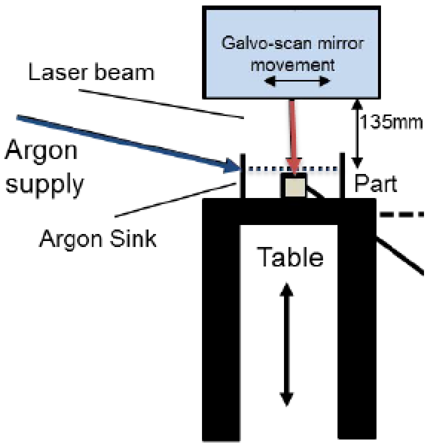
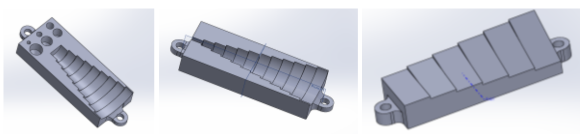


Figure 1. Laser polishing set-up

2.2 Database Framework

A number of both flat and complex parts were produced with typical AM features seen in the aerospace industry (see Figure 2). The parts were then processed using two targeted techniques – laser polishing and automated abrasive finishing. The laser polishing was performed using the same set-up as described in Section 2.1. The automated abrasive finishing was performed using an ABB IRB4600 robotic arm with IRC5 controller, fitted with an ABB large 6 DOF force-torque sensor. The part was held to the robotic arm using a pneumatic gripper, and delivered to a stationary Amtru pneumatic FlexFinisher200 fitted with a quick-fit tool changer. The set-up is shown in Figure 3. A range of abrasive brushes were trialled (Table 1), and manually loaded into the FlexFinisher tool. Appropriate attack angles and forces were used and resulting surface finishes were recorded in order to collate the key process variables (KPVs) into the database framework.

Figure 2. Example complex AM geometries used to create database



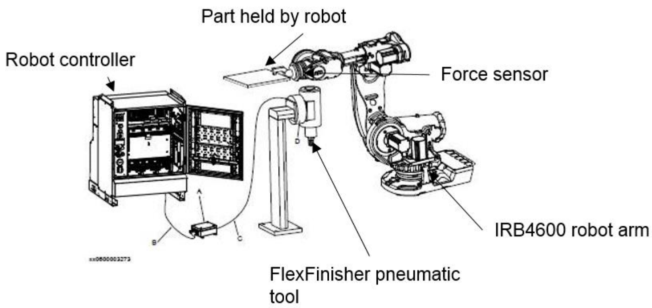


Figure 3. Automated abrasive finishing set-up

Table 1 Abrasive brushes assessed in trials

Abrasive Brush	Sizes (d – diameter, t – thickness)	Grit Specification
Xebec Fibre XSM-06 - 25 Sleeve	6mm – 25mm (d)	Blue (coarse)
Xebec Cross-hole Grit Ball XCHB	3mm – 6mm (d)	#220 (coarse)
Xebec Short Shank XCHM	10 mm (d)	Blue (coarse)
3M Unitised Wheel	38mm (d) x 3 mm (t)	XCS and MED (coarse to medium)
3M Unitised Wheel	75mm (d) x 6mm (t)	XCS and MED
339 Flap Wheel	30mm (d) x 15mm (t)	P60 – P120 (coarse to medium)
339 Flap Wheel	60mm (d) x 30mm (t)	P60 – P120

3. Results and Conclusions

A predictive model based on the DOE trials which outputs the expected surface roughness of Ti6Al4V SLM parts following laser polishing has been created, this allows the user to select optimum parameter sets based on; the desired surface roughness, the starting as-built roughness and the feature thickness. The results demonstrate that laser polishing can reduce surface roughness by at least 90%, and up to 99% with multiple passes and cooling strategies. For example a starting roughness of ~30µm can be reduced to ~1µm in the first pass, and an areal roughness of 300nm has been achieved with multiple passes. The current validation model for In718 SLM can predict the final finish (Sa) to within 7% of the actual measured value, and with more experimental data to be assessed this is expected to improve.

A knowledge platform has also been created for two emerging techniques (laser polishing and automated abrasive finishing) based on the key process variables revealed in the experimental work, this framework is demonstrated in Figure 4. This highlights the experimental data from both targeted abrasive finishing and laser polishing, and how this data will be fed into the AM process chain. The experimental results for abrasive finishing demonstrate that from a starting areal roughness of ~25µm, a reduction to ~2µm can be achieved; with further improvements expected from additional optimisation. The data behind the feedback loops will be used to create a design tool in the CAD space; inputting the constraints based on this experimental data to further develop a line-of-sight model into a 'smart' tool. This is demonstrated on two processes in Figure 4 but can be expanded to more. The key process variables are summarised in Table 2

allow these techniques to access the more complex geometries that additive manufacturing allows in these applications.

Figure 4. Database framework and feedback into AM process chain

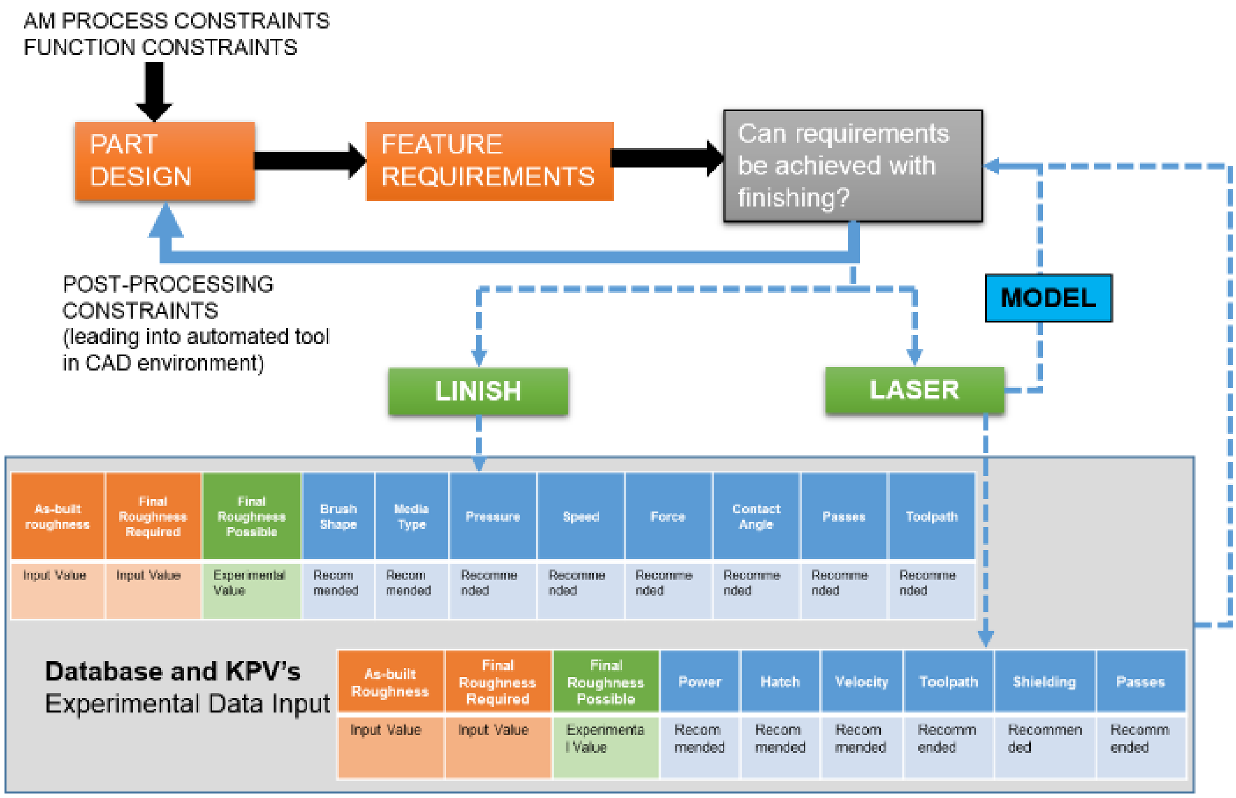


Table 2 Key Process Variables

Laser Polishing KPVs	Abrasive finishing KPVs
Power (W)	Brush Size and Shape (mm)
Hatch (µm)	Media Type (grit)
Scan speed(mm/s)	Pneumatic Pressure (bar)
Toolpath	Speed (m/s)
Shielding (l/s)	Contact Force (N)
Passes (no. of)	Contact Angle (deg)
Dwell time	Passes (no. Of)
	Toolpath

In summary, experimental data for laser polishing of Ti6Al4V and In718 has been used to create a predictive model for surface roughness based on the laser parameters; power, hatch and velocity. Alongside this, experimental data collected on both laser polishing and mechanical abrasive finishing has been collated into a database of parameters with associated achievable surface roughness, allowing the user to gain expert knowledge through this framework. The development of targeted and automated finishing techniques addresses the industry need for reduced manual processing for complex AM parts and also forms the basis of improving the AM design process chain, to allow the inclusion of targeted finishing processes in the CAD stage. The results shown here also demonstrate that the techniques presented can achieve finish standards demanded by the aerospace industry, typical S_a values range from 1.6µm for non-critical applications, to 0.8µm for fatigue loaded parts. However, further work will be required to

4. Future Work

Further work investigating the compatibility of the laser polishing model on different materials and powder bed processes is required to allow wider impact on a variety of aerospace alloys and processes.

More data on both laser polishing and abrasive finishing should be collected to allow investigation of the impact of build angle and orientation within the AM process. The integration into a CAD design tool of the knowledge platform and laser polishing model is also necessary to allow full 'design for finishing' capability in the AM process chain.

It is recognised that feature-based metrics and a combination of surface parameters is often more descriptive for AM surfaces, and as such further analysis on these parameters to compare them to S_a is planned. For example investigation into kurtosis and skewness has been undertaken, and these are useful for assessing the distribution and form of surface asperities that laser polishing aims to remove.

References

[1] Smith, B., Hiersemenzel, H., See, T., (2016) Laser polishing of additively manufactured steel and titanium components, *Joint ASPE and EUSPEN Conference on Dimensional Accuracy and Surface Finish in AM,* Raleigh, USA

[2] Gibson, I., Rosen, D., Stucker, B. (2010). *Additive Manufacturing Technologies*: Rapid Prototyping to Direct Digital Manufacturing, Springer, 2010

[3] Zeng, K. (2015). *Optimization of support structures for selective laser melting,* University of Louisville, PhD Thesis, Aug 2015

[4] Bauer, J., and Malone, P. (2015). Cost estimating challenges in additive manufacturing, *ICEAA 2015*
[5] Hemsoth, N. (2012) Additive Manufacturing's Dirty Secrets Exposed. [online] Available at: http://www.enterprisetech.com/2012/11/21/additive_manufacturings_dirty_secrets_exposed/ [Accessed 19 Jan. 2016]
[6] Wohlers (2015). Wohlers Report 2015, 3D Printing and Additive Manufacturing State of the Industry, *Annual Worldwide Progress Report,* ISBN: 978-0-9913332-1-9
[7] Fraunhofer ILT (2016). [online] Available at: http://www.ilt.fraunhofer.de/en.html [Accessed 20 Jan. 2016]
[8] AM SRA, (2014). *AM Platform, Additive Manufacturing Strategic Research Agenda 2014*
[9] Temmler, A., Putsch, O., Stollenwerk, J., Willenborg, E., Loosen, P. (2014). Optical set-up for dynamic superposition of three laser beams for structuring and polishing application. *Optical express,* **22(2),**1387-1393
[10] Jamal, M., Morgan, M.N. & Peavoy, D. (2017) A digital process optimization, process design and process informatics system for high-energy abrasive mass finishing. *Advanced Manufacturing Technology*
[11] Gorana, V.K., Jain, V.K. & Lal, G.K. (2006) Prediction of surface roughness during abrasive flow machining. *Advanced Manufacturing Technology*, **31: 258**. doi:10.1007/s00170-005-0197-4