EXPERIMENTAL FRAMEWORK FOR TESTING THE FINISHING OF ADDITIVE PARTS

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ABSTRACT

Selective laser melting (SLM) is a metal additive manufacturing (AM) process involving the selective layer-wise scanning of a powder bed. It is capable of producing metal parts for applications including the aerospace and medical industries. However, components made by SLM are currently not always reaching their potential in industry, due to limitations in the process leading to inadequate part quality. One particular example is the attachment of partially melted particles to the surface which can act as crack-initiation sites reducing part fatigue life. It is therefore necessary to find finishing processes for metal AM parts that remove these particles without compromising the advantages of AM. This paper presents the challenges of finishing AM parts, outlines techniques reported in the literature, and proposes an experimental framework for analysing the effectiveness of finishing processes for AM. The outlined framework will help improve the scientific understanding of finishing processes for AM.

Keywords: Additive manufacturing, Surface roughness, Finishing processes.

1 INTRODUCTION

SLM is a powder-bed additive technology in which metal powder is evenly distributed across a build platform by a blade or roller (Kruth et al. 2010). A laser is then used to selectively melt the powder based on geometry data from a CAD file (Löber et al. 2013). After each layer is scanned, the platform is lowered to allow for the next powder layer to be deposited. The process enables complex geometries with internal channels and features to be produced from high performance materials such as Ti-6Al-4V, making a whole new realm of design possibilities available to industry. AM allows designs to be optimised to significantly reduce the number of parts and joining processes required, hence impacting both weight and durability. It also reduces the amount of waste produced compared with machining because parts are built from powder which, when left un-melted, can be sieved and reused (Wohlers 2014).

There are several barriers currently hindering SLM from becoming adopted for the production of functional parts for critical applications. Many of the material properties greatly differ from those produced by conventional manufacturing techniques and due to the relative infancy of SLM, there is still limited understanding of the mechanisms which influence the part properties. In many applications where parts are cyclically loaded, fatigue life is a particular concern and can be detrimentally affected by micro-cracks and poor surface properties. Depending on the material used, a surface roughness value, R_a, of between 7.6-15.2μm can be expected for parts built by laser-based powder bed AM processes such as SLM (Wohlers 2014). However for many applications this is inappropriate, and R_a values of as low as 2μm or less are often required, particularly in the aerospace industry (Dadbakhsh et al. 2010). It is therefore necessary to develop a technique to achieve the required surface quality of SLM parts.

This paper presents a novel methodology for analysing the appropriateness of potential candidate AM finishing techniques. The authors recognise that in order to fully evaluate the effects of a finishing process on a given part, a number of material properties need to be assessed. The focus of this work is surface roughness as this provides an initial indication of the removal or modification of the material at the surface, which directly relates to a number of functional properties (Pyka et al. 2013). The proposed methodology will be used to analyse a number of existing AM finishing techniques. By assessing their strengths and limitations, further refinements to existing processes or entirely new processes will be explored. These processes will then be rigorously analysed, by testing a more extensive range of material properties and allowing for a standardised testing method for AM finishing processes to be developed.

2 SURFACE ROUGHNESS IN SELECTIVE LASER MELTING

The surface roughness of an SLM-produced part is influenced by a combination of the processing parameters and the part geometry. Laser power, spot size, scanning speed, scan strategy, hatch distance, layer thickness and powder particle size are among the variables which can be applied to a particular build, and influence the surface morphology of each layer (Yadroitsev et al. 2007; Pupo et al. 2013). This affects not only top surface roughness, but also the interaction between subsequent layers and the presence of pores in the material (Kruth et al. 2010). The interactions between processing parameters are highly complex and lead to non-linear changes in surface morphology (Yadroitsev & Smurov 2011). It is currently not possible to simultaneously optimise top and side roughness caused by the melting process due to the balling phenomenon (Mumtaz & Hopkinson 2009).

A phenomenon known as the “stair-step effect” governs the surface roughness of inclined and curved surfaces which are approximated for AM to allow them to be built up in layers. This is inherent to the manufacturing technology, but can be reduced by using smaller layer thicknesses. At low sloping angles, the stair-step effect accounts for the majority of the surface roughness. However, at higher sloping angles where the distance between step edges is similar to the particle size, surrounding powder can be partially melted and bonded to the part due to conduction of heat from the edges (Strano et al. 2013). These concentrations of partially-bonded particles cause an increase in surface roughness, and introduce a potential to break away from the part during use, which in many applications could have disastrous consequences.

In order to control the surface quality of parts produced by SLM, finishing processes are required which can remove partially-bonded particles and reduce surface roughness. However, many conventional finishing processes are limited to simple or external geometries and if used, would negate the use of AM to build the parts in the first place. Any finishing techniques which require line-of-sight are unlikely to be suitable for parts with internal features. However, with such a range of possible geometries, a thorough testing method is needed to assess potential candidate finishing processes.

3 FRAMEWORK FOR TESTING OF FINISHING PROCESSES

This section presents the proposed framework for the experimental work. Figure 1 presents the stages of work, which map onto the proceeding subsection headings.

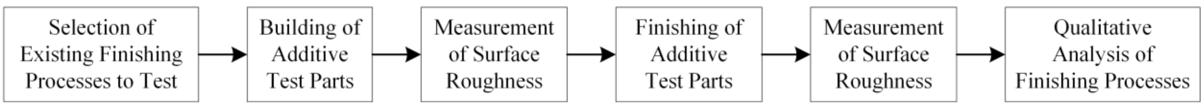


Figure 1: Outline of stages for proposed methodology.

3.1 Selection of Existing Finishing Processes to Test

Having surveyed salient literature relating to the finishing of AM parts, a number of perceived issues have been noted and Figure 2 combines these with a number of additional issues envisaged by the authors, marked by a (*). The inclusion of these items is based upon consideration of the application of reported processes in an industrial setting. All of the issues mentioned will be considered when selecting finishing processes to test, but particular consideration will be given to the flexibility in terms of the geometries that can be finished. This is because the extent to which a process can finish complex and particularly internal geometries is considered inherent to the nature of the process.

Flexibility		
Can the process finish parts containing freeform surfaces? (Beaucamp et al. 2014)	Can the process finish parts containing internal features? (Pyka et al. 2012)	Is the process material-specific? (*)
Controllability		
Does the process preferentially treat surfaces? (Pyka et al. 2013)	How repeatable is the process? (*)	Can the process be controlled to achieve a predefined Ra value? (Pyka et al. 2013)
Preservation of Parts		
Does the process change the part material properties? (Spierings et al. 2013)	Is there potential for contamination from finishing media? (Farayibi et al. 2015)	How can the parts be fixtured/traced throughout the process? (*)
Practicality		
Does the process introduce any health and safety concerns? (*)	Can the process be automated? (Dadbakhsh et al. 2010)	Can the process be integrated with additional manufacturing processes? (*)

Figure 2: Perceived issues for finishing AM parts.

3.2 Building of Additive Test Parts

There is no single test part used in literature for the testing of finishing processes for AM parts. Most experimental work uses 2.5D geometries to measure the reduction in surface roughness achieved by the finishing processes. This gives an initial indication of the appropriateness of a process and provides an easily measureable surface for roughness parameters which are comparable with the literature.

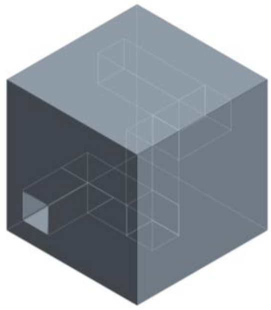
As previously explained, the roughness of a surface and the number of partially-bonded particles on the part is highly dependent on the part geometry. Therefore testing only the top surface of a 2.5D geometry is insufficient for determining the suitability of a finishing process for AM parts. Because of the nature of AM providing opportunities to produce highly complex geometries and internal features, it is important that any finishing process is able to access every surface. Strano et al. (2013) used a test part with sloping angles ranging from 0-90° for comparing experimental surface roughness with predictions from a theoretical model. It is proposed that a similar geometry will be used in this work to analyse the influence of initial surface roughness on the effectiveness of the finishing processes.

Pyka et al. (2012; 2013) used a porous lattice-like structures to test the surface finishing capability of a chemical etching process. These structures enabled the ability of the liquid to access and treat internal surfaces to be tested. This work will incorporate a test part with internal geometries, to prove whether or not each process will support this critical benefit of AM technology.

The proposed experimental work will consist of several stages of testing, beginning with simple 2.5D geometry and finishing with a case study part containing internal geometries from a potential industrial end-user. Table 1 shows the proposed stages of the experimental work in terms of increasing geometrical complexity, with proposed example features which aim to test the flexibility of processes.

The processing parameters will be kept consistent for all test parts and will be based on previous optimisation carried out by the SLM machine manufacturer. The material used in all tests will be Ti-6Al-4V in order to directly compare processes that have previously been tested on different materials.

Table 1: Test part geometries to be used for each stage of the experimental work.

Stage #	Purpose of stage	Example Geometry
1	Proof of concept and optimisation of finishing process parameters.	
2	• Analysing effect of changes in as-built surface. • Testing ability to finish complex external features.	
3	Testing ability to finish internal features.	
4	Real part designed specifically for SLM containing: • Freeform surfaces • Internal features • Predefined surface requirements for industrial application	CASE STUDY PART

3.3 Measurement of Surface Roughness

In order to quantify and compare the effectiveness of the finishing processes, the surface roughness will be measured both before and after finishing. Although roughness parameters do not fully capture the characteristics of the surface profile, they do provide a quantifiable representation of the quality of surface finish (De Chiffre et al. 2000). R_a, the arithmetic mean deviation of the profile, is the most commonly used 2D roughness parameter in industry and it is also used in many papers in this field to quantify surface roughness (Löber et al. 2013; Farayibi et al. 2015; Mingareev et al. 2013). In this work, a white-light surface profilometer will be used to create 2D and 3D profiles of the surfaces to allow both 2D and 3D roughness parameters (R_a and S_a) to be recorded. This will allow the work to be compared to current research (Dadbakhsh et al. 2010), as well as providing detailed information about the finished surfaces and the capabilities of each process.

In this work, it is important not only to quantify the surface quality but to also analyse the surface morphology and identify the reasons for the measured roughness parameters. In particular, the presence of partially-bonded particles is significant for determining whether the finishing processes are suitable for critical applications where contamination can be catastrophic. Scanning electron microscopy (SEM) will therefore be used to obtain images of the surfaces, in order to qualitatively assess the surfaces and help with understanding and comparing the finishing processes.

3.4 Finishing of Additive Test Parts

The finishing processes to be tested will be selected from those reported in the literature. This subsection presents the key literature published to date in this area. The classification of deburring operations as determined by Gillespie (1999) can be easily adapted for surface finishing processes for additive parts, as shown in Figure 3. This is not an exhaustive list but shows the range of techniques that have been reported.

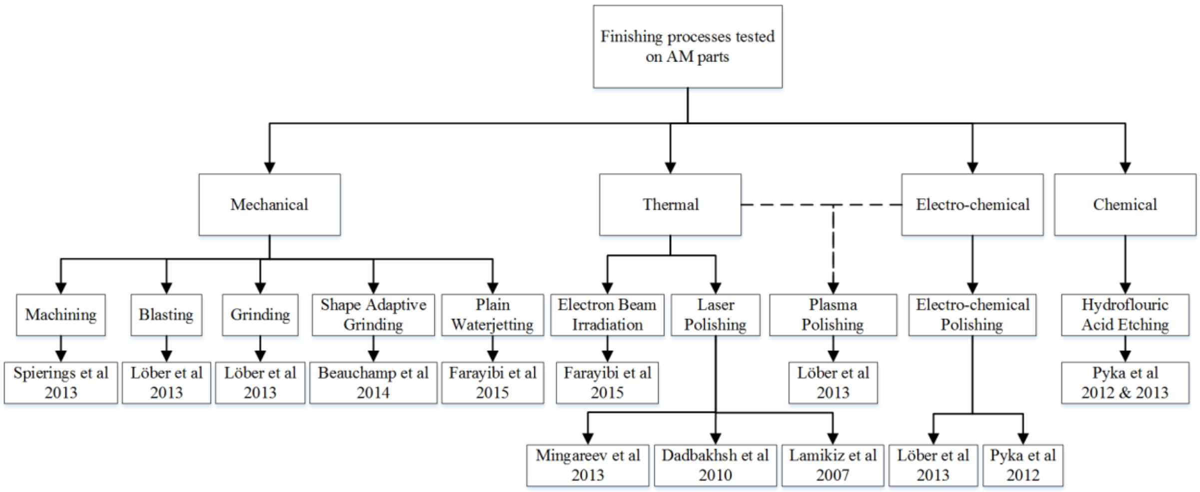


Figure 3: Classification of previously reported finishing processes for metal AM parts.

Mechanical processes involve applying forces to the outer surface of the part causing partially sintered powder to break away from the part. In industry, finishing of AM parts is often carried out by conventional machining methods (Wohlers 2014). Spierings et al. (2013) reported a surface roughness parameter R_a = 0.4µm on SLM-produced 316L stainless steel finished by machining.

Thermal processes involve melting the peaks of material on the surface in order to fill the gaps, producing a more uniform surface. Surface roughness parameters R_a < 3µm have been reported following laser post-processing of SLM parts (Mingareev et al. 2013).

Chemical processes involve using etchants which react to the exposed particles, removing them from the part surface. Using SEM imaging, Pyka et al. (2013) showed that etching using hydrofluoric acid (HF) solution was able to remove partially-bonded powder particles from the surface of SLM-produced Ti-6Al-4V porous structures. Increasing treatment time and HF concentration caused greater reductions in surface roughness.

Electro-chemical processes combine electrical current which removes electrons from the part surface, and chemical electrolyte which dissolves the metal ions as they are released. Löber et al. (2013) measured the surface roughness of SLM parts following electro polishing. An R_a value of 0.21µm was achievable for an electro polishing process which was preceded by grinding.

3.5 Analysis of Finishing Techniques

The primary factor in the analysis will be the surface roughness measurements from each of the experimental stages. The SEM images will be used to understand the processes and to identify their strengths and limitations. The issues shown in Figure 2 will be used to determine the appropriateness of the processes following the testing procedure. The presented criteria will be weighted based on their perceived importance, and observations from the experimental work will be used to determine the extent to which each process meets each criterion. Once the processes have been compared, the data will be used to formulate a plan for further testing.

4 CONCLUSIONS & FUTURE WORK

Metal AM technologies introduce many new possibilities into manufacturing however, part qualities are currently inappropriate for many critical applications. The surface roughness of parts is of particular concern when considering the fatigue life, and suitable finishing processes are needed that are capable of treating the surfaces of geometrically complex parts. Although a number of techniques have been presented in the literature, many consider only 2.5D geometries or consider limited issues relating to the finishing of AM parts. This paper outlines an experimental framework for comparing and analysing the appropriateness of finishing processes for SLM-produced parts. The data obtained from this work will be used to determine further testing requirements, such as measurement of fatigue life of finished parts, and will provide a dataset against which any potential candidate processes could be compared.

ACKNOWLEDGMENTS

The authors are pleased to thank the Engineering and Physical Science Research Council (EPSRC No. EP/L505341/1) and our industrial partner for their support during this research.

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