Evaluation of the metal additive manufacturing process through the study of the recyclability of metal powder and in-situ metrology.

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ABSTRACT
Powder bed fusion (PBF) additive manufacturing (AM) processes are becoming frequently applied within a wide range of industries, allowing production of complex, high-value components. Direct metal laser sintering (DMLS) is a PBF process commonly used within the medical device and aerospace industries where regulations drive the requirement for stringent quality control.

Powder material used in the DMLS process can be costly, and as it is rare for a full batch of virgin powder to be used in one build, it is frequently recycled for subsequent builds. Therefore, it is useful to characterise both the powder material being recycled and the final component properties being produced. Characterisation of the recycled powder and the parts produced allows the feasibility of powder recycling to be assessed.

Furthermore, the ability to monitor and measure the components as they are being built layer-by-layer during the process enables the quality of the components to be assessed. Using in-situ monitoring, the identification of defects as well as measurement of the layers throughout a build allows for greater quality control, as well as a reduction in the requirement for ex-situ measurement.

Results from this work provide PBF operators with detailed knowledge of the effect that recycled powders have on the quality of the components produced as well as providing a method to monitor the component layer-wise throughout the process. This will facilitate a more controlled use of PBF within the highly regulated industries.

INTRODUCTION
The additive manufacturing process is a research area which, in recent years, has received increased attention due to its ability to produce complex parts which previously were not possible through conventional subtractive manufacturing processes [1]. Additive manufacturing is the process of joining materials layer-by-layer to produce complex, often high-value parts for the aerospace, automotive and medical device industries [2, 3]. EOS 316L stainless steel is a stainless steel powder commonly used for these applications offering highly corrosion resistant parts [4]. The additive manufacturing process presented in this research is the powder bed fusion (PBF) process of Direct Metal Laser Sintering (DMLS), shown in Figure 1. This process selectively melts a powder bed, layer-by-layer to build a final part. The powder layer is deposited on the build platform by the recoater arm. The laser then melts the powder layer and a new layer of powder is deposited. The process repeats layer-by-layer until the part is complete.
The powder material (metal) for the process is produced through atomisation and is generally spherical in shape with a diameter range of 10 and 80 µm for additive applications [3]. The powder material is often costly, costing up to €500/kg for titanium alloys for example; therefore, recycling the powder for subsequent builds is desirable [5]. Powder recycling is defined as the practice of collecting the un-melted powder after a build and reusing it for subsequent builds [6]. The process of recycling leads to changes in the powder characteristics as well as affecting the quality of the parts produced [2, 6]. The industries applying PBF are often required to adhere to stringent quality procedures and standards. Hence, understanding how the feedstock metal powder develops through the recycling process is required to maintain full traceability within the AM process, while increasing the usable life of a costly consumable [7].

The ability to monitor the quality of the parts as they are being produced is also a requirement for many of these regulated industries. This area of research has been identified as one in need of significant attention [8]. Using in-situ monitoring allows for in-process defects to be identified and quantified during the build process [9]. Quantifying the defect will allow for a decision to be made on the impact of the defect on the final integrity of the part. The application of in-situ monitoring can also be used to observe the consistency of the powder deposition process in DMLS. Consistent and repeatable powder deposition is vital for the successful outcome of the process [10].

A lack of quality assurance in additive manufacturing is currently a technological barrier for manufacturers to adopt the additive processes [9]. Monitoring the powder material through the multiple stages of recycling and adopting an in-situ monitoring system within the DMLS process enables quality assurance to be applied to the process.
METHODOLOGY

Powder Recycling
The effect of powder recycling on the powder characteristics and the resulting part qualities produced has been investigated for EOS 316L Stainless Steel powder. Powder recycling consists of collecting the un-melted powder deposited on the build platform and in the overflow region (see Figure 1), and sieving it at 63µm. The sieved powder is then reused in subsequent builds. Sieving ensures that oversize particles are removed from the powder before it is reintroduced into the process.

Characterisation of the powders after each build provides an insight into the performance within the AM process and also, how the recycling of such powder material affects the chemical composition, size and morphology of the powder. The characterisation methods applied to the powder material were, energy dispersive x-ray (EDX) for chemical composition, laser diffraction for particle size distribution and scanning electron microscopy with image analysis for particle morphology assessment.

Five different parts were printed for each reuse of the powder, as presented in Figure 2. The parts were designed to allow for the following quality tests to be conducted; white light interferometry for surface roughness measurement, CNC measurement for dimensional accuracy of parts, Rockwell hardness for part hardness and finally micro-sectioning to allow for analysis of part density. The part quality results have been compared to the corresponding EOS 316L material data sheet [4].

All measurements were repeated three times and an average obtained. The error associated is represented using the standard error of the mean (SE) calculated, as follows:

\[ SE = \frac{\sigma}{\sqrt{N}} \]  

(1)
Where: $\sigma$ is the standard deviation of the measurement and $N$ is the number of repeat measurements for each test [11].

_In-situ Monitoring_

A novel standalone monitoring system, as shown in Figure 3, consisting of a monochrome camera, laser trigger capture sensors and controller has been installed into the build chamber of the EOS M280. The aim of this installation is to enable the build process to be imaged, layer-by-layer. These images are currently assessed post-build in to order to identify defects in parts or inefficiencies in the powder deposition process.

![Camera](image)

Figure 3: Standalone in-situ camera installation showing the area of interest (Dashed blue area).

The camera captures two images per layer, one after the new powder has been deposited and the other, after the laser exposure has been completed. Python and ImageJ are used to post-process the images and extract the required information. This enables a record for each individual layer of the build to be created for quality control purposes. Defects that are identified can also be assessed in terms of their impact on the integrity of the produced parts. The aim of this work is to develop a method of real-time in-situ monitoring for the EOS M280.

**RESULTS AND DISCUSSION**

_Powder Recycling_

A total of 11 builds have been completed using a 30kg batch of EOS 316L powder for this study. This has exposed the powder to the DMLS process conditions for a total of 111 build hours. Throughout this recycling, the powder’s chemical composition showed no significant sign of
deviation from the manufacturer’s stated chemical composition. Figure 4 (a) shows that as the recycling process increases, the mean particle size increases. This is due to the ease at which smaller particles are melted in the process and can lead to many larger particles (those greater than the layer thickness) being pushed by the re-coater arm in the overflow region.

Figure 4 (b) shows that with an increase in powder reuse, the circularity of the powder deteriorates; this can be attributed to the agglomeration of smaller particles to the larger ones resulting in non-circular particles. A circularity value of 1 indicates a perfectly circular particle.

Figure 4: Effect of increased powder build hours due to powder recycling on (a) mean powder size and (b) powder morphology.

It is well understood that the characteristics of the powder material affect the properties of the parts that are produced [2, 12]. However, there are limited studies quantifying this effect. This research has found that as the powder is recycled more frequently the part qualities deteriorate in all measured qualities, except hardness. As powder recycling increased, it was found that the surface roughness of AM parts increased, while the dimensional accuracy and density of these parts both decreased significantly.

The correlations between the powder particle size and part density, and the powder morphology and part surface roughness are presented in the following graphs. Figure 5 (a) shows that as the mean particle size increases the part density decreases ($R^2 = 0.955$), this is evident in examinations of the micro-sections of the density cubes. There is an increased number of larger pores present. This can be explained by the disruption to the powder deposition process due to the lack of smaller particles
present in the batch which can be used to fill in the gaps in the rough surface of the previous melted layer. This is shown schematically in Figure 6 below.

Figure 5 (b) shows the deterioration in the surface roughness beyond the specification, of $13 \pm 5 \mu m$, provided on the manufacturer’s data sheet [4], particularly in the last seven data points. This correlated well ($R^2 = 0.828$) with the decrease in the circularity of the particles. As less circular and larger particles are melted during the process, this causes a rougher surface to be produced.

In-situ Monitoring

Prior to the development of a program to assess the images, a control chart was developed in order to inform the operation of the image analysis program. The aim of the control chart is to allow for
decisions to be made on the quality of the powder deposition or the laser exposure. These defects are common features in failed DMLS builds. Each build with a defect will have different outcomes; however, some of the defects associated with the deposition of the powder material are shown in Figure 7 below.

![Examples of commonly observed defects in the DMLS process](image)

**Figure 7:** Examples of commonly observed defects in the DMLS process (a) Re-coater Vibrations, (b) inclusions in powder bed and (c) Lack of powder deposition

The post-processing of the images allows for defects in the powder layering process and laser exposure process to be identified. At present, the images are assessed after the build and provide the ability to identify how a defect began as well as enabling the impact of the defect to be assessed. In future, this will be further developed as a real-time monitoring system with defect detection.

**CONCLUSION**

The results from this work have to date highlighted two key issues:

1. Powder recycling leads to a change in the powder characteristics which in turn impact the quality of the parts produced through the DMLS process.
2. In-situ monitoring has been used to identify defects in the build process through the imaging of the build platform before and after laser exposure.

These findings provide significant information for regulatory-driven industries where continual quality control and assurance is required. The ability to track and monitor the quality of the feedstock material and the ability to monitor the build process in-situ will enable greater process quality control.

Further research will be conducted to determine the effect of powder recycling on the powder density through pycnometry and the powder flowability through hall flow tests. A study on powder mixing
with the aim to rejuvenate the recycled powder material for continued usage will be conducted. This will involve mixing the recycled powder with new virgin powder material to restore the powder characteristics in bulk. The aim of this is to investigate the effect of mixing on the powder characteristics and the part qualities, leading to more efficient use of powder material.

Development of the defect detection process will provide real-time monitoring and assessment of the images. This will enable the process to be used as a decision tool for the operator to enable them to assess the development of defects early in the build process.

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REFERENCES


