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Optical in-situ monitoring and correlation of density and mechanical properties of stainless steel parts produced by selective laser melting process based on varied energy density

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In-situ monitoring systems for additive manufacturing processes drive the possibility for identification of defects during printing, rendering both time and cost savings as the process can be stopped if a failure is detected. However, the relationship between defects identified during printing to the actual mechanical performance of the printed part has yet to be established. In this paper, we report the design and development of an optical based image processing in-situ monitoring system implemented on the selective laser melting process. The system consisted of an optical camera, a mirror and a set of light emitting diode lights. 316L stainless steel specimens were fabricated with varying energy densities. Features captured in the optical images during printing were identified and quantified by image processing techniques. Results from density tests based on Archimedes' principle and mechanical properties from tensile tests have demonstrated a correlation with the processed optical images of the specimens, validating the potential of inferring mechanical performance of printed parts based on features identified through the optical based image processing in-situ monitoring system.

Keywords: In-situ monitoring; Additive manufacturing; Image processing;
Selective laser melting; Mechanical properties

1. Introduction

Chua et al. (2017) defined additive manufacturing (AM) as the process of fabricating objects from a three-dimensional (3D) computer-aided design (CAD) data where materials are deposited layer-by-layer. Hiemenz (2014) reported the wide adoption of AM in the aerospace industry throughout all processes and functions; from design conceptualization to near-end-of-life repair. He discussed the AM trends in this industry, citing applications in the production of jigs, fixtures and unmanned aerial systems. Inagaki et al. (2014) examined the applications of pure titanium and titanium alloys in the aerospace sector. They stated that high-performance titanium alloys, in particular, Ti-6Al-4V, is favored for the manufacturing of advanced aerospace structures such as engine parts. Alysia et al. (2016) investigated the supply chain of AM materials. The reported growth in the sales of metals for AM is driving the need for research of metallic materials. Close to half of the AM equipment sales are attributed to industrial machines, motor vehicles and aerospace components, where these sectors have an indispensable need for metals.

AM of metals is commonly actualized through powder bed fusion (PBF) processes, such as selective laser melting (SLM). In SLM, a thin layer of powder is deposited on the build platform by a powder recoating system. A high intensity laser is used as an energy source to selectively melt and fuse regions of powders in a layer-by-layer fashion, in accordance to the CAD data. Upon completion, the building platform is lowered, a next layer of powder is deposited on top, and the laser scans a new layer. The sequence of depositing and scanning is repeated until the part is fully built.

While PBF processes allow design freedoms unequalled by conventional manufacturing methods, production techniques require strict control of processing parameters and conditions to build a part of high quality. As many printing parameters are involved in an SLM process,

defects are inevitably generated when any of these parameters are inappropriately selected. To that end, researchers generally resort to experimental studies, simulations and monitoring methodologies to achieve high quality printed parts.

Vast amounts of literature are available on the optimization of metallic components printed by SLM. Some of the studies include investigations on the optimal energy density to produce parts with the best mechanical properties, selection of a suitable design for support structures to minimize thermal warpage of printed components and topology optimization to produce lighter metal components. Song et al. (2012) studied the melting mechanisms of Ti-6Al-4V powders by varying the printing parameters of the SLM process. They successfully printed Ti-6Al-4V parts with high density that is comparable to the bulk Ti-6Al-4V alloy, high microhardness and a smooth surface finish using optimized laser power and scanning speed for the SLM process. Gan and Wong (2016) examined three types of support structures for their effectiveness in maintaining the levelness of each printed layer. They also determined the minimal number of contact points needed between the overhangs and the main part to minimize the extent of thermal distortion. Seabra et al. (2016) employed topology optimization to the printing of an aircraft bracket by SLM. They performed metrological and mechanical tests to validate the design of the component. The optimized component had considerable reduction in weight and an increased factor of safety.

A myriad of works has also been published on simulations related to SLM. Tang et al. (2018) studied the underlying physics involved in the formation and propagation of near-spherical and irregular-shaped porosities during melting and solidification of the SLM process. They developed a high-fidelity 3D model to simulate the single-track formation of 316L stainless steel during printing. Multilayer simulation was subsequently carried out to investigate how

porosities accumulated through each layer. Le et al. (2018) analyzed the effect of adopting different scanning strategies—sequential and boustrophedon on the melt pool behavior and levelness of the printed surface. They conducted single-track and multi-track simulations and concluded that sequential scanning strategy produced a non-flat printed surface while the boustrophedon strategy can produce a flat printed surface. Tan et al. (2018) investigated the characteristics of porosities and their distributions within the printed part by using unoptimized energy densities for their computational model. They simulated the melting and solidification process of 316L stainless steel powders by SLM. Irregularly shaped porosities tend to form near the top surface of the powder bed while spherical and elliptical porosities were located at the bottom of the keyholes. These results were consistent with experimental results. The melt pools' width and depth evaluated by simulation were consistent with experimental results.

While experimental studies are important, they can be influenced by internal or external factors that may alter the outcomes being achieved. The materials, machines and processing parameters reported in literature papers vary across research groups, which may affect the reproducibility and accuracy of the results if the same experiment is replicated by end users or individuals. This is a major concern for experiments involving the optimization of mechanical properties of printed parts. It is sometimes technically challenging to obtain identical powder feedstock as described in literature papers. SLM machines manufactured by different companies may have different allowable range of processing parameters, such as laser power, posing difficulties for the replication of processing parameters to match the reported values in literature papers. The accuracy of the results obtained from experimental studies is also dependent on the experience of the operator. Human intervention is needed for the preparation of the machine and powder bed before printing. Powders laid onto the substrate before printing must be uniform to

ensure the quality of the printed part. Inexperienced operators may neglect the need to level the substrate, thereby affecting the adhesion of the first few layers of the print to the substrate.

Similarly, although simulation studies indeed can provide important insights into understanding the process and melt pool characteristics, and the ability to predict the formation of defects during the SLM process, the accuracy and the applicability of extending the results to actual printing remain uncertain. Assumptions made in simulations, such as adiabatic boundary conditions, are unable to fully capture the dissipation of heat through the entire powder bed during real-time printing. Furthermore, despite the importance of simulations in examining defects formation during printing, limitation to the size of computational domain questions the relevance of the results when scaled up to the size of actual printed parts and manipulation of multilayer simulations to match the real printing conditions of hundreds to thousands of layers will be computationally expensive.

In-situ monitoring systems for AM processes, however, drive the possibility for identification of defects during printing. This renders both time and cost savings as the process can be stopped if a failure is detected. Semi built parts that do not meet the standards can be stopped automatically before further parts are manufactured. As the systems monitor the actual printing process, the results are representative of the printed part and no extrapolation or scaling is needed as in the case for simulations. However, the correlation between defects identified during printing and the mechanical properties of the printed part must be studied for the development of a robust in-situ monitoring system. This information is vital as it bridges the gap between the defects identified by the monitoring system and the actual performance of the part. Some commercial in-situ monitoring systems feature the capturing of images layer by layer for inspection of defects. EOS GmbH (2017) introduced EOSTATE MeltPool – an automated and

real-time process monitoring system for direct metal laser sintering. During the build process, monitoring is carried out at each layer and each part. EOSTATE MeltPool software registers data by measuring light emitted by the melt pool, which can be used to draw conclusions on the presence of defects in printed parts. Other systems enable the visualization of defects through the stacking of images from the start to the end of the print job, similar to that of a computed tomography (CT) scan. Concept Laser GmbH (2015) developed an in-situ quality assurance system, QMmeltpool 3D that utilizes coaxial sensors to identify the melt pool area and the melt pool intensity. The system documents position-related characteristics of the melt pool when the part is being printed, providing local indications of defects in the part. A 3D image illustrating the locations and sizes of defects in the printed part is generated after the build process. Despite the advancement of commercial in-situ monitoring systems in defects detection, the impact of these defects on the structural integrity of the printed part remains unknown. Since the optical resolution of these systems is not publicly available, the correlation between captured images and structural integrity of the printed parts can only be established through high-resolution imaging. This enables fine details of the printed and recoated layers to be captured before accurate quantification of defective regions can be performed for correlation with the parts' mechanical properties. Foster et al. (2015) developed a high-resolution powder bed monitoring system using a consumer grade digital single lens reflex (DSLR) camera to compare the acquired images of parts with actual characteristic defects generated during printing. They designed a series of cylinders with intentional variation of laser power and hatch spacing to create lack-of-fusion defects. Non-uniform linear perturbations in the powder layer due to dragged agglomerated powder were observable in the captured images. Craeghs et al. (2011) implemented a visual inspection system for powder deposition using a high-speed complementary metal oxide

semiconductor camera to examine the wear and local damage of the recoater blade. The system is able to detect small scratches distributed throughout the powder bed and local deep scratches of the powder bed. However, the effects of these defects identified during printing on the density and mechanical properties of the printed part have yet to be adequately investigated by researchers and industrial experts.

Ultimately, the performance of a printed part is dictated by its density and mechanical properties. Yet, many research works and commercial systems focus only on the defects identifiable during in-situ monitoring of the SLM process. There is, however, a crucial need in establishing the relationship between defects identified during printing to the actual mechanical performance of the printed part for advancements in the development of in-situ monitoring systems. In this work, we report the design and development of a high-resolution in-situ monitoring system to identify and quantify features from the optical images captured during the SLM process of printed parts. These were then compared and correlated with their densities and mechanical properties. Image processing algorithms were used to segregate the features present in the optical images. Known variables were used to quantify the features captured in optical images. A relationship between the number of features present in optical images captured in-situ and the mechanical properties of parts determined after printing was validated and established. This can potentially aid in the production of parts with better mechanical properties. Printing parameters can be adjusted in-situ to improve the quality of the printed part if the number of features present in optical images correlate to weak mechanical properties, rendering both time and cost savings.

2. Development of the in-situ monitoring system

The in-situ monitoring system comprises a separate set of equipment installed onto the SLM machine to monitor the printing process. The system is independent on the different brands of SLM machines and is highly portable.

2.1 Equipment

The machine used in this study was SLM 500 from SLM Solutions, consisting of four IPG fibre lasers, each with a power of 400 W and beam focus diameter between 80 and 115 μm . The size of the substrate used was $248 \times 248 \times 25$ mm. Light emitting diode (LED) light strips were installed onto the chamber walls of the machine to achieve uniform lighting during image capturing. The Nikon D500 DSLR camera, placed outside of the machine, was used to capture optical images during the printing process. A photointerrupter was affixed to the chamber wall at a height above the homing position of the recoater to automate the capturing of optical images during printing.

An optical mirror was mounted at an angle of 45° between the walls of the chamber by a tensioning rod to direct the optical light path of the DSLR camera from the exterior to the powder bed inside the chamber. The field of view provided by the mirror measures 60×40 mm. It was mounted near the front door of the SLM chamber (Figure 1). The laser path has been marked out using strings and the mirror was placed outside of this boundary. This prevents the mirror from interfering with the laser beam during printing.

Achieving uniform lighting within the chamber of the machine, as highlighted by Foster et al. (2015), is the most critical factor to obtain optical images with sufficient contrast for image processing and to automate the process of defects detection. They developed an optical in-situ monitoring system with multiple flash modules for the SLM process and concluded that the

capturing of surface defects is dependent on the intensity and positioning of these modules. Although there is one set of in-built white LED lights installed at the SLM 500 chamber ceiling, it does not provide sufficient illumination resulting in images with poor intensity and contrast. Hence, in this work we considered the use of additional white LED lights as the solution to achieve uniform illumination within the chamber, as illustrated in Figure 1.

Figure 1. Placement of mirror, in-built and additionally installed white LED lights inside machine chamber

2.2 Achieving uniform lighting

Two lighting conditions were considered for evaluation — (1) in-built white LED light in the SLM 500 chamber and (2) additionally installed white LED lights without in-built lighting. Both conditions made use of LED lights as they provide diffuse illumination, reducing non-uniform illumination in the chamber. The positioning of the additionally installed LED lights was focused on the area near the front door of the SLM 500 chamber. Although the platform has an area measuring 280×500 mm for printing, the field of view for monitoring the print area is 60×40 mm based on the current experimental set-up.

As space is a constraint within the chamber, especially at the ceiling due to the presence of the laser and camera viewports, the additional LED lights were placed close to one another to maximize the illumination. The LED lights were also installed without diffusers due to the limitation of space which would otherwise further improve the uniformity of illumination in the chamber. The histograms of the images captured were mainly used for evaluation. The images of the object being captured should theoretically be uniformly lit and have a histogram with intensity values widely spread out across the 256 gray levels.

2.2.1 In-built LED lighting

Since there is only one set of in-built LED light at the SLM 500 chamber ceiling, optical images captured for each layer were generally dark in intensity as seen in Figure 2 (a). According to the histogram in Figure 2 (b), the intensity of the light source is low as the peak value of intensity is at 63. Furthermore, the image contains only a fraction of the total range of gray levels with intensity values falling between 30 to 216, indicating that there is inadequate contrast between the printed parts and the unmelted powders.

(a)

(b)

Figure 2. (a) Grayscale image of printed parts and (b) histogram of grayscale image for printed part under in-built LED lighting

2.2.2 Additional LED lights

A separate print was carried out in which additional sets of white LED light (without using the in-built white LED light) were installed at the ceiling and the side walls of the chamber to achieve uniform lighting (Figure 1) and obtain images with high contrast. An improvement in the intensity of the light source and contrast of the captured image can be observed by comparing Figures 3 (a) and 2 (a). Furthermore, the histogram in Figure 3 (b) illustrates that the intensity value peaks at 98, indicating an improvement in the intensity of the light source as compared to the use of in-built lighting. The contrast of the image has been significantly enhanced with the use of additionally installed LED lights as the intensity values spread across a wider range from 42 to 255 as observed in Figure 3 (b). Hence, the additionally installed white LED lights were used during in-situ monitoring of the SLM process.

(a)

(b)

Figure 3. (a) Grayscale image of printed parts and (b) histogram of grayscale image for printed part under additional sets of LED light

2.3 Imaging resolution test

The modulation transfer function (MTF) was used to evaluate the performance of the optical system. MTF evaluates the performance of an optical system by integrating resolution and contrast (modulation) information into a single parameter. Dereniak and Dereniak (2018) reviewed that when the spatial frequency of line-pair per unit length (resolution) increases, it becomes increasingly challenging for an optical system to effectively resolve each line-pair of resolution. It also means that the modulation of the image degrades. The MTF was determined using the 1951 United States Air Force (USAF) target as shown in Figure 4.

Figure 4. 1951 USAF target

Common aberrations such as coma, spherical aberration and astigmatism can be effectively reduced by stopping down the aperture (increase f/number) of the lens. Stopping a

lens to higher f/number also increases depth of field. This helps to lessen tilt aberration which is prominent in an off-axial monitoring system. The primary trade-off of stopping down a lens is less light throughput and more diffraction blur due to the inverse proportion of diffraction limit to f/number. These opposing factors indicate an ideal f/number at which optical aberrations and diffraction blur are compromised to yield an optimal image quality. The ideal aperture stop is determined by plotting the MTF curves with various f/number. Figure 5 shows the images and close-up details of 1951 USAF resolution target captured by our optical system at various aperture stops. Blurs from optical aberration such as astigmatism and tilt are prominent at small f/number (wide aperture) while diffraction blur is influential at large f/number (small aperture).

Figure 5. Images and close-up details of the 1951 USAF resolution target captured at various f/number

Since the proposed monitoring system is off-axial in nature, its MTF was measured at both the center and corner of the DSLR camera's field of view to find the ideal aperture stop for images taken at a given depth of field. The optical system was focused at the center of the field of view and the exposure is kept constant for all aperture settings. Figure 6 illustrates the MTF of

the optical system. Aperture stop f/22 was chosen as the optimum f/number for the monitoring system.

Figure 6 (a). MTF of the optical system at center of the DSLR camera's field of view

Figure 6 (b). MTF of the optical system at corner of the DSLR camera's field of view

3. Materials and methods

3.1 Powder material

316L stainless steel powders were used in this research. The chemical compositions of the powders are listed in Table 1. The powders have a spherical shape with diameters ranging from 20 to 53 μm .

Table 1. Chemical composition of as-used 316L stainless steel powders

Element	Fe	Cr	Ni	Mo	Mn	Si	O	C
Content (wt.%)	Balance	16 to 18	11 to 14	2 to 3	≤ 2.0	≤ 1.0	0.062	≤ 0.03

3.2 Design of specimens and printing parameters

Thijs et al. (2010) examined the influence of energy density on the microstructure of Ti-6Al-4V alloy processed by SLM. They noted the presence of martensitic and intermetallic phases when the rectangular specimens were printed with different energy densities. However, a more detailed study relating the effects of energy density on the occurrence of defects during printing is needed. Energy density E (in Jm^{-3}) is defined as the average applied energy per volume of material during the scanning of a powder layer and is computed as

$$E = P / (v \cdot h \cdot t) \quad (1)$$

where P is the laser power (in Js^{-1}), v is the scanning speed (in ms^{-1}), h is the hatch spacing (in m) and t is the powder layer thickness (in m).

In this investigation, the laser power and scanning speed were varied while hatch spacing of 0.14 mm and layer thickness of 50 μm remained constant throughout the experiment. Hence, the energy density is expressed as a ratio between the laser power and scanning speed. Based on preliminary experiments, a laser power (P) of 175 W and scanning speed (v) of 550 mm s^{-1} were considered as the reference data set, denoted as $E_{P,v}$. Details of the preliminary experiment can be found in the supplementary material.

Ten sets of 316L stainless steel specimens were fabricated by the SLM process. Each set of specimens consisted of a cylinder and a sub-size tensile coupon. The cylindrical specimens are 8 mm in diameter and 8 mm in height. Sub-size dog bone shaped tensile coupons were printed with dimensions in accordance to ASTM E8 / E8M-15a as shown in Figure 7 (ASTM E8 / E8M-15a, 2015). The images of the cylinders were captured by the in-situ monitoring system. Tensile tests were carried out to determine the ultimate and yield strengths of the tensile coupons. The results based on the optical imaging of the cylinders will be correlated to the density and mechanical properties of the cylinders and tensile coupons respectively. Table 2 shows the scanning parameters used for printing each set of specimens. The printed cylinders are shown in Figure 8.

Figure 7. Dimensions of sub-size tensile coupon in millimeters

Table 2. Printing parameters for ten sets of specimens and their energy density ratios

Specimen	Laser power (W)	Scanning speed (mms^{-1})	Notation	Energy density ratio
I	87.5	550	$E_{0.5P,v}$	0.5
II	175	1100	$E_{P,2v}$	0.5
III	175	550	$E_{P,v}$	1.0
IV	350	1100	$E_{2P,2v}$	1.0
V	175	367	$E_{P,0.67v}$	1.5
VI	87.5	550	$E_{1.5P,v}$	1.5
VII	175	275	$E_{P,0.5v}$	2.0
VIII	350	550	$E_{2P,v}$	2.0
IX	350	367	$E_{2P,0.67v}$	3.0
X	350	275	$E_{2P,0.5v}$	4.0

Figure 8. Cylinders printed by the SLM process

Before the start of the print job, an initial image of the uniformly coated powder bed is captured. During printing, two images are captured for each layer of powder deposition for the printing of the cylinders — one after scanning but before recoating, and another after recoating of the scanned layer. These optical images are then post processed by image processing algorithms for features identification and evaluation. The evaluation of features by image processing algorithms for each cylinder will be used to correlate with the mechanical properties of the respective tensile coupons.

3.3 Archimedes' density test

Density measurements of the printed cylinders were carried out using the Mettler Toledo XS204 analytical balance with a specific density measurement device for solid materials.

Vandenbroucke and Kruth (2017) investigated the use of SLM as a rapid manufacturing technique for medical applications. They printed titanium alloy blocks and measured the density according to Archimedes' principle in which the mass of a solid is measured in air and subsequently in an auxiliary liquid with known density. The liquid used in this case is ethanol. The density of the solid can be calculated based on

$$\rho = A/(A - B) \times (\rho_0 - \rho_L) + \rho_L \quad (2)$$

where ρ is the density of the solid (in gcm^{-3}), A is the mass of the solid in air (in g), B is the mass of the solid in the auxiliary liquid (in g), ρ_0 is the density of the auxiliary liquid (in gcm^{-3}), and ρ_L is the density of air (in gcm^{-3}).

3.4 Tensile test

Sub-size dog bone shaped tensile coupons of 316L stainless steel were printed in $x - y$ (flat) direction and removed from the steel substrate using wire electrical discharge machining. Tensile tests were carried out in displacement control using an Instron 8501 universal testing machine at room temperature. An axial extensometer of 10 mm gauge length was attached to the gauge region of the tensile specimens for strain measurements. Displacement rate of crosshead was set at 1 mm/min. Tensile yield strength was determined by an offset yield point at 0.2% strain.

4. Image processing and features quantification

The optical images of the cylinders after recoating for each layer were used for image processing and analysis. An image captured during the printing process is shown in Figure 9. These photographs were captured in grayscale and saved as 8-bit intensity images in TIFF format. The range of the 8-bit intensity images is between 0 to 255. A grayscale intensity value of 0 and 255 represents black and white pixels respectively.

Figure 9. Recoated layer of powder bed captured during printing

Features captured in the optical images are represented by pixels that are either brighter or darker than that of the powders as illustrated in Figure 9. While in an ideal case, the powder bed should be uniformly recoated with powders after the scanning of each layer, i.e., there should not be any features elevated from the surface of the powder bed after recoating (Figure 10 (a)), features may arise from factors such as argon gas flow rate and the variations in printing

parameters during the actual printing process. Their presence may be an indicator to the quality of a print. Information such as the number, area and location of the features can be extracted from the optical images captured after each layer of recoating for a print. MATLAB was used for image processing (MATLAB, 2018).

4.1 Extraction of features from optical images

The initial layer of a uniformly recoated powder bed is captured as the background image before printing starts (Figure 10 (a)). The background image acts as a uniform target since the metal powders are of the same reflectivity and are laid evenly on the substrate. It is needed to account for any non-uniformity of illumination in the captured images. The region of interest (ROI), where each cylinder will be printed is defined by a binary mask, as shown in Figure 10 (b). The white pixels of the mask are used to enclose the image processing algorithms within the ROI. The average grayscale intensity value, I_{avg} , of the initial image is calculated for the area within the ROI. The region will then be filled with the average grayscale intensity value to produce an image, N_0 , which will be used as a reference for subsequent image processing (Figure 10 (c)).

The black pixels of the binary mask are overlaid onto the optical image of the recoated layer as illustrated in Figure 10 (d). The absolute difference will be taken between each optical image of the recoated layers (Figure 10 (c)) and the reference image (Figure 10 (d)). This step is crucial as any non-uniformity of illumination in the captured images is subtracted away using the reference image, where the latter is derived from the background image. It should be highlighted that despite efforts made to ensure the uniformity of illumination, the edge of the camera's lens and the absence of diffusers for the LED lights will inevitably cause regions in the images to be non-uniformly lit. The corners of the captured images, for instance, appeared darker as seen in Figure 10 (a). While a non-uniformly lit background image (recoated powder bed) will directly

influence the average grayscale intensity value of the reference image, the extraction of features from the optical images will not be affected. The important information revealed is represented by the absolute difference between the captured image of each recoated layer and the reference image, and not the average grayscale intensity value itself. The resulting image highlights the presence of features represented by pixels that are of higher grayscale intensity values (brighter) than the background (Figure 10 (e)). Contrast-limited adaptive histogram equalization is then applied to the image to enhance the contrast between the features and the background (Figure 10 (f)). The grayscale intensity range of the image is stretched to reveal more details of the features and allow these features to be distinguished at different illumination levels. The last step of features extraction involves thresholding of the resultant image using the maximum entropy method to obtain binary images, where white pixels represent the features of each recoated layer as seen in Figure 10 (g). The flowchart in Figure 11 summarizes the image processing algorithms used to extract features from the optical images. The features extraction process was performed separately for every cylinder. The layer thickness for each layer of print was 50 μm . Hence, optical images were captured after every 50 μm .

Figure 10. (a) Initial layer of recoated powder bed used for calculation of average grayscale intensity value at ROI, (b) binary mask for image processing at ROI, (c) reference image, N_0 , ROI is filled with average grayscale intensity value, (d) black pixels of mask overlaid onto one of the cylinders (ROI), (e) revelation of features after difference is taken between (c) and (d), (f) features highlighted after contrast-limited adaptive histogram equalization is applied and (g) binarized image containing features after thresholding

Figure 11. Image processing algorithms for features extraction from optical images

The scanning strategy of the SLM machine requires the contour of the part to be scanned before the rest of the regions are scanned, resulting in the presence of porosities at the perimeters. It is therefore worthwhile to note that the perimeters of the cylindrical specimens were omitted for image processing due to the inherent porosities as shown in Figure 12. As such, the mask, represented by the white pixels in Figure 10 (b), covers only 85% of the original cross-sectional area of each cylinder in order to omit the evaluation of porosities near the perimeters.

Figure 12. Optical micrograph showing the cross-section of a cylinder with circled porosities present at its perimeter

5. Results and discussions

5.1 Density and tensile tests

The densities of the ten cylinders based on Archimedes' principle and ultimate and yield strengths of the tensile coupons are shown in Figure 13.

Figure 13. Densities, ultimate and yield strengths of ten specimens

Based on the results from Archimedes' test, a general trend shows that an increase in the energy density ratio from 0.5 to 2.0 leads to an increase in the density of the cylinders. Following which, the density remains relative constant for cylinders with energy density ratios of 3.0 and 4.0 as the powders are fully melted. It should be noted that the densities of cylinders II and IV are lower than cylinders I and III respectively. Despite having the same energy density ratio, a

higher scanning speed has resulted in cylinders II and IV being less dense than their counterpart specimens.

The ultimate strength and the yield strength of the ten tensile coupons were measured and shown in Figure 13. Both properties exhibit an increase in value with an increase in energy density ratio of the tensile coupons from 0.5 to 2.0. Following which, the ultimate and yield strengths exhibit a slight decrease for tensile coupons of energy density ratios 3.0 and 4.0. Similarly, tensile coupon IV has notably lower ultimate and yield strengths as compared to tensile coupon III of a same energy density ratio.

As the high energy laser scans across the powder bed for specimens VIII to X, the melting and solidification process are completed within an appreciably short period of time, generating a huge temperature gradient and a high stress field. An immense amount of residual thermal stress is accumulated in the fabricated specimen. The thermal energy accumulated in the printed layer cannot be dissipated rapidly in materials with low thermal conductivity. As a result, cracks are formed to release the stresses as seen in Figure 14. These transverse cracks reduce the load-bearing section of the tensile coupons and act as stress concentration sites, reducing the ultimate and yield strengths. Density, on the other hand, remains relatively high as the high laser power ensured sufficient energy input into the melt pool to fully melt the stainless steel powders.

Figure 14. Scanning electron microscopy images of cylinders (a) IX and (b) X illustrating the presence of cracks

5.2 Image processing

The area of features captured in the optical images after each layer of recoating is correlated to the density measurements from Archimedes' test. Optical images used for analysis are in binary form and the area of features is expressed as a percentage of its ROI for each layer. Each cylinder is analyzed individually by cropping them out for a total of N number of layers. The number of layers for each print job depends on the height of the parts. The total area of white pixels of the mask (Figure 10 (b)) is equivalent to the cylinder's region of interest for each layer, denoted by P_{total} . The total area representing the features (or simply, the white pixels in Figure 10 (g)) for each layer is denoted by $P_{i,features}$, where i corresponds to the layer number. The percentage area of features for each layer, $\varphi_{i,features}$ is defined as

$$\varphi_{i,features} = P_{i,features} / P_{total} \times 100 \quad (3)$$

The average percentage area of features for each cylinder, $\varphi_{features,average}$, is expressed as

$$\varphi_{features,average} = \frac{\sum_{i=1}^N \varphi_{i,features}}{N} \quad (4)$$

The average percentage area of non-features for each cylinder, $\varphi_{non-features,average}$ is defined as

$$\varphi_{non-features,average} = 100 - \varphi_{features,average} \quad (5)$$

The percentage area of features for every layer of the ten cylinders is shown in Figure 15. In general, it can be noted that an increase in the energy density ratio from 0.5 (specimens I and II) to 2.0 (specimens VII and VIII) leads to lower percentage area of features for the cylinders. However, the percentage area of features for cylinders II and IV are notably higher than that of other cylinders. A significant portion of the layers for these two cylinders fall in the range nearer to their upper limits, suggesting the presence of a substantial area of features.

Figure 15. Percentage area of features present in each layer for ten cylinders

It should be noted that the imaging processing results for cylinder IV indicated an extensive number of features present. Indeed, this could be due to the direction of argon gas flow and the positioning of cylinder IV during the printing process. Cylinder IV is at the left-most position as compared to the other cylinders. As the argon gas flows from right to left within the machine chamber, process by-products such as vaporized powders (condensates) that are removed tend to accumulate on the left side of the chamber (Figure 16). Moylan et al. (2013) presented a summary on the safety and environmental issues on metal AM and examined these condensates. The condensates, which tend to appear darker than that of the background, are oxides of the metal formed, contributing to the presence of darker pixels in the optical images. Liu et al. (2015) investigated the spattering behavior during SLM of 316L stainless steel powders. Energy dispersive spectroscopy analyses of fresh 316L powders and spatter particles revealed a higher oxygen content for the latter. These powders react with remaining oxygen in the chamber, generating iron oxides.

Figure 16. Condensates accumulated on the left of powder bed

The condensates build up as the print proceeds after each layer of recoating, resulting in non-uniform heating when the laser beam is directed at the powder bed. This leads to significant amounts of elevated regions in cylinder IV. The excessive presence of features in the recoated layer of cylinder IV is evident from the optical image in Figure 9. Foster et al. (2015) also captured optical images illustrating uneven powder layers due to elevated regions, causing a change in the physical interaction of the laser beam with the material, leading to inconsistency in processing and sometimes, porosity. Consequently, the density of cylinder IV is reduced.

The build-up of condensates is prominent for cylinders VIII to X printed with high energy densities as seen by trails of dark particles concentrated at the left side of the specimens in Figure 3 (a). However, their densities are not significantly reduced and their percentage area

of features are low based on the results from Archimedes' test and image processing. This is attributed to the high energy density during printing, which ensured complete melting of the metal powders.

5.3 Correlation of results

Figure 17 (a) depicts the average percentage area of non-features for each cylinder and their densities. Figure 17 (b) illustrates the average percentage area of non-features for each cylinder and the ultimate and yield strengths of the respective tensile coupons. These two figures provide an overview on the relationships established between the results of image processing and mechanical properties of the specimens.

Figure 17 (a). Average percentage area of non-features and densities of ten cylinders

Figure 17 (b). Average percentage area of non-features, ultimate and yield strengths of ten specimens

The results from image processing indicated that cylinders I, II and IV, having relatively higher percentage area of features, displayed poorer mechanical properties as illustrated by Figures 15 and 13 respectively. Therefore, these cylinders had lower average percentage area of non-features, translating to lower densities, ultimate and yield strengths as seen in Figures 17 (a) and 17 (b). Cylinders III and V to X, having relatively lower percentage area of features, exhibited better mechanical properties as illustrated by Figures 15 and 13 respectively. Correspondingly, these cylinders had higher average percentage area of non-features, translating to higher density, ultimate and yield strengths as illustrated in Figures 17 (a) and 17 (b). The aforementioned relationship has demonstrated the feasibility of using the proposed in-situ

monitoring system to infer the density and mechanical properties of printed specimens based on the percentage area of features in optical images. Specimens with relatively higher percentage area of features have poorer mechanical properties while specimens with relatively lower percentage area of features have better mechanical properties.

5.3.1 Specimens I, II and IV

Specimens printed with a relatively low energy density ratio of 0.5 had printing parameters set to either low laser power (specimen I) or high scanning speed (specimen II). Gu et al. (2013) studied the influence of energy density on porosity formation in 17-4 precipitation hardening stainless steel parts produced by SLM. They demonstrated that a relatively low laser power may cause insufficient penetration to the previous solidified layer for the attachment of newly formed liquid metal particles, resulting in poor wetting. In addition, lower laser power also decreases the probability of powder ablation and plasma formation near the surface of the powder bed, reducing the overall absorptivity of the metal powders.

A relatively high scanning speed reduces the allowable time that the laser beam is in contact with each powder particle which may otherwise ensure complete melting. The outcome of these various effects is an increase in the presence of unmelted and partially melted powder particles, reducing the overall density of the printed specimens. X-ray micro CT imaging of the ten cylinders revealed a large amount of porosities in cylinders I, II and IV as illustrated in Figure 18. There are also extensive regions of partially melted powders present in cylinders I and II. The metallurgical bonding between layers are weakened, affecting the structural integrity of the tensile coupons.

Figure 18. Micro CT images of cylinders showing the presence of porosities

The effects of printing specimens with relatively low energy density ratio and high scanning speed are well reflected in the optical images captured by the in-situ monitoring system. Balling and instability of the melt pool results in regions of the printed parts to be elevated from the surface of the powder bed, represented by pixels that are brighter than that of the powders. The presence of features in the optical images of cylinders I, II and IV are more pronounced than that of the remaining cylinders evident from the higher percentage area of features in Figure 15. Cylinder I has percentage area of features within 1–5%. Cylinders II and IV have percentage area of features in the range of 0–14% and 0–17% respectively. The density, ultimate and yield strengths of specimens I, II and IV, as discussed, are significantly lower than the rest of the specimens as seen in Figure 13. It can be concluded that cylinders with higher percentage area of features exhibit lower densities and weaker mechanical properties. Hence, the implementation of the in-situ monitoring system enables end users to distinguish specimens with relatively lower density and weaker mechanical properties.

The significantly lower densities and higher percentage area of features of specimens II and IV illustrated the influence of scanning speed on the densification of printed parts in SLM process. A high scanning speed results in reduced surface energy of the liquid and instability of the liquid track. Numerous small-sized liquid droplets tend to splash from the surface of the molten track. The build-up of these liquid droplets may cause uneven recoating of the metal powders and formation of elevated regions during printing, translating to brighter pixels in the optical images.

5.3.2 Specimens V to X

According to equation 1, with the hatch spacing and layer thickness kept constant, specimens of relatively high energy density ratios (with values ranging from 1.5 to 4.0 in this study) can be printed by setting the printing parameters to either high laser power (specimens VI and VIII) or low scanning speed (specimens V and VII) or a combination of both (specimens IX and X). A relatively high laser power ensures sufficient energy input into the melt pool to fully melt the stainless steel powders.

Kasperovich et al. (2016) established a correlation between the processing parameters and porosity formation in selective laser melted Ti-6Al-4V specimens. They reviewed that a low scanning speed reduces the shear stress of the liquid phase of the metal, decreasing the surface tension within the melt pool. As a result, wettability between the molten metal and the underlying printed layer or substrate is enhanced, minimizing the occurrence of balling and discontinuities forming on the melt track. The balling phenomenon is the separation of melt pool into small spheres. The spattering of molten metal droplets caused by high scanning speeds which contribute to the formation of porosities will also be lessened in this case. The result is a

diminution in the amount of unmelted powder particles and porosities. Hence, the overall density of the printed specimens increases.

As discussed, the formation of discontinuities in specimens is reduced as the energy density increases. The corresponding tensile coupons can sustain higher tensile stress when lesser amounts of defects are present within the structure. Significantly lesser amounts of defects are seen in the micro CT images of cylinders III and V to X (Figure 18), leading to higher measurements in their ultimate and yield strengths.

The improved stability of the melt pool due to increased energy density is notable from the optical images captured by the in-situ monitoring system. The powder bed is more uniformly recoated as compared to printing specimens with relatively low energy density. This is supported by a low percentage area of features for cylinders V to X, which falls within 2% across all layers as depicted in Figure 15. The occurrence of features in the optical images of these cylinders are drastically reduced as compared to cylinders I, II and IV. The printed layers of the cylinders do not have pronounced elevated regions (brighter pixels) and condensates (darker pixels) in the optical images. It can be concluded that cylinders with lower percentage area of features exhibit higher densities and stronger mechanical properties. The implementation of the in-situ monitoring system enables end users to distinguish specimens with relatively higher density and better mechanical properties.

6. Conclusion

A high-resolution in-situ monitoring system has been installed onto the SLM machine to identify and quantify features in optical images captured during the SLM process of printed parts for correlation to their density and mechanical properties. The use of additional sets of LED lights instead of in-built LED lighting ensured uniform illumination and improved intensity within the chamber for capturing of images with adequate contrast.

Ten sets of specimens, each consisting of a cylinder and tensile coupon, made of 316L stainless steel were designed with varying energy densities through different combinations of laser power and scanning speeds. The cylinders were monitored during the SLM process and optical images were captured before and recoating for every layer of the print job. An image processing algorithm was introduced to extract features from these optical images and subsequently quantify them for correlation with density tests of the cylinders and mechanical properties of the tensile coupons based on Archimedes' principle and tensile tests respectively.

The implementation of the self-developed in-situ monitoring system enables end users to distinguish specimens with relatively higher density, ultimate and yield strengths. These specimens were printed with relatively high energy density ratios ranging from 1.5 to 4.0. They exhibited low percentage area of features which fell within 2% across all layers. The relatively high laser power or low scanning speed or a combination of both ensured complete melting of the metal powders and reduced the probability of discontinuities from forming, thereby increasing the overall density and mechanical properties of the specimens. The improved stability of the melt pool reduced the occurrence of elevated regions in each printed layer, ensuring a more uniformly recoated powder bed. Hence, the presence of features in the optical images decreased.

Conversely, the implementation of the self-developed in-situ monitoring system enables end users to distinguish specimens with relatively lower density, ultimate and yield strengths. These specimens were printed with a relatively low energy density ratio of 0.5. They exhibited high percentage area of features ranging from 0–17% across their layers. These specimens printed with relatively low energy density were more susceptible to the incomplete melting of the metal powders. The presence of partially melted and unmelted powder particles reduced the density and structural integrity of these specimens. Balling and instability of the melt pool results in regions of the printed parts to be elevated from the surface of the powder bed, represented by pixels that are brighter than that of the powders. Hence, the occurrence of features in the optical images increased.

The effect of scanning speed, which has been demonstrated to significantly affect the density and mechanical properties of printed specimens can be inferred based on the percentage area of features captured in optical images. Despite having the same energy density ratio of 1.0, cylinder III had a much higher density than cylinder IV as the latter was printed with double the scanning speed. A similar trend was observed between cylinders I and II. A possible reason for the low mechanical properties of specimen IV is the accumulation of condensates on its surface due to its placement on the substrate and the direction of argon gas flow, causing excessive amounts of elevated regions to be formed. These elevated regions translate to notably high number of features captured in the optical images after each layer of recoating.

The findings in this paper have demonstrated feasibility of inferring the density, ultimate and yield strengths of the specimens printed with varying energy densities based on optical images captured during in-situ monitoring of the SLM process. It enables end users to distinguish between specimens with relatively higher and lower densities and mechanical

properties. If image processing of these optical images is performed in real-time, end users have the flexibility to decide on the continuance of a print based on the percentage area of features for the specimen.

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Declaration of interest: none.

Supplementary material

Three 316L stainless steel cubes with the parameters shown in Table were printed and their densities measured by Archimedes' principle. The density of the 316L stainless steel powders is 7.985 gcm^{-3} . The selection of a reference parameter was based on the density of the printed cube that is at least of 97% of the reported value. Hence, the printing parameters of cube III was chosen as a reference.

Table S1. Preliminary results for density of printed 316L stainless steel cubes

Cube	Laser power (W)	Scanning speed (mms^{-1})	Density (gcm^{-3})	Percentage density (%)
I	87.5	550	7.013	87.8
II	175	1100	7.182	89.9
III	175	550	7.797	97.6

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