Additive Manufacturing 22 (2018) 601–605

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Full length article

Thermal near infrared monitoring system for electron beam melting with emissivity tracking

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ARTICLE INFO

Keywords:
Thermal imaging
Electron beam melting
Process monitoring

ABSTRACT

This paper presents the design of a high speed, high resolution silicon based thermal imaging instrument and its application to thermally image the temperature distributions of an electron beam melting additive manufacturing system. Typically, thermal images are produced at mid or long wavelengths of infrared radiation. Using the shorter wavelengths that silicon focal plane arrays are sensitive to allows the use of standard windows in the optical path. It also affords fewer modifications to the machine and enables us to make use of mature silicon camera technology. With this new instrument, in situ thermal imaging of the entire build area has been made possible at high speed, allowing defect detection and melt pool tracking. Melt pool tracking was used to implement an emissivity correction algorithm, which produced more accurate temperatures of the melted areas of the layer.

1. Introduction

Additive Manufacturing (AM) is a rapidly developing, yet comparatively immature manufacturing technology [1]. AM parts are created directly from precise Computer Aided Design (CAD) models and currently suffer from dimensional variations, rough surface finishes, and internal defects not present in those models. These issues present a barrier for uptake amongst the advanced manufacturing sectors most likely to benefit from the design freedom AM brings; for example, aerospace and automotive. One potential solution to these issues is advancement of in-process monitoring systems. AM processes typically rely upon heat to fuse particles of deposited materials. Thermal imaging is, therefore, ideal for AM in-process monitoring. Progress so far in this field has concentrated on the use of mid and long wavelength infrared (IR) imaging technologies [2,3].

Common thermal imaging products and systems use focal-plane-array (FPA) technologies that include InSb detectors [3] and microbolometers [2]. These are sensitive to mid-wavelength IR (MWIR) (3–5 µm) and long-wavelength IR (LWIR) (7.5–14 µm), respectively. Typical, high-end thermal cameras produce images with VGA resolution (640 × 480) and frame rates of 9–15 Hz. Silicon FPAs are sensitive to visible wavelengths of optical radiation and are ubiquitous in consumer imaging products. Although silicon FPAs are usually optimised for visible wavelength sensitivity (400–700 nm), their responsivity spectrum has significant sensitivity in the near infrared (NIR), which typically extends across 750–1050 nm. The maturity of silicon as an optical radiation sensitive material and the huge volume of silicon FPAs that have been developed, has led to silicon out performing other FPA technologies. For example, it is common to find multi-megapixel silicon detectors that produce fast (> 60 Hz) or ultra-fast (> 1000 Hz) frame rates.

AM is a demanding application for thermal imaging; particularly Electron Beam Melting (EBM). Imaging must not only be sufficiently high resolution to show the formation of variations from CAD models, it must also be sufficiently high speed to capture the time-resolved interaction of the electron beam with metal powder. We, therefore, decided to use mature silicon technology for our AM thermal imaging.

Our AM system is of the EBM type and was developed by Arcam [4]. The process in the Arcam A2 is similar to other metal AM processes, specifically powder bed fusion (PBF); where a 3D object is built layer by layer, using an electron beam as the input energy source. The use of an electron beam, in preference to a laser, allows the beam to be steered across the build area at a very high speed, using electromagnetic deflection coils (Fig. 1). This contrasts with the slower mechanical parts found in other approaches to AM and dictates a higher speed monitoring solution is needed for effective use of this technology. The use of an electron beam necessitates the process to operate under vacuum and with elevated bed temperatures to sinter the powder before melting. These requirements have advantages in reducing the chamber oxygen content and residual stresses in the parts when compared with standard

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https://doi.org/10.1016/j.addma.2018.06.004
Received 22 March 2018; Received in revised form 7 June 2018; Accepted 10 June 2018
Available online 15 June 2018

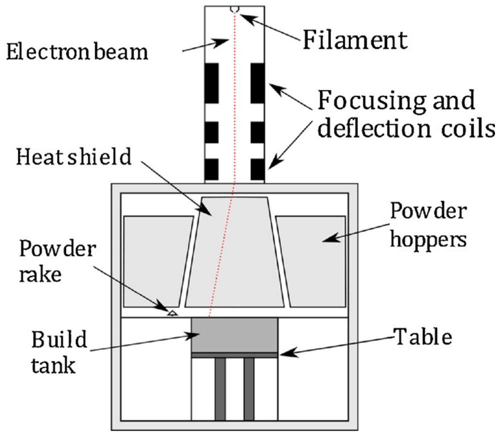

Fig. 1. Arcam A2 EBM system diagram.

laser processes [5]. The vacuum itself does not pose any problem for thermal imaging, however, the system design had to take this into account by ensuring any parts mounted to the vacuum chamber made an adequate seal. The elevated bed temperature is much lower than the temperature at which the powder melts (1003 K vs 1933 K for Ti-6Al-4 V) and so the cooling rates are significant; hence the instrument measurement range must cover a very wide temperature range. The current state of in-process monitoring for AM is limited, especially for the EBM process. Most of the work on comprehensive monitoring systems is at the research stage [2,3], with only Arcam's LayerQam [6] technology available commercially.

2. Materials and methods

2.1. Instrument design

The thermal imaging instrument comprised a Hamamatsu C11440-22CU silicon sCMOS camera [7], sensitive to wavelengths from 400 nm to 1 µm and with a resolution of 2048 × 2048 pixels. A custom designed 'borescope' lens system was produced, together with a redesigned vacuum chamber mount and Kapton film feed system. This provided an alignment mechanism for the borescope and prevented metallisation of the window behind which the borescope is mounted. The borescope lens design allowed the camera to be mounted away from the vacuum chamber (Fig. 2). This gave easy access for imaging with minimal modification to the Arcam A2. Significant modifications were not recommended due to the risk of X-Ray radiation generated within the process. A consequence of this was the need to use lead glass in the optical system. Imaging in the NIR allowed us to do this because the transmission of the glass at this wavelength range is > 90% (reducing to 76% when combined with the Kapton film), compared to 1.08% found by R. B. Dinwiddie et. al [3]. when imaging in the MWIR.

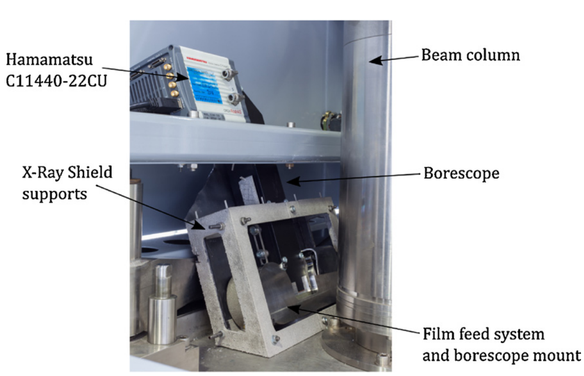

Fig. 2. Full instrument mounted on Arcam A2.

Therefore, the camera could be used at its full potential with low exposure times and high framerates. It also allowed imaging through all phases of the build, unlike E. Rodriguez et. al [2]. where a shutter was used to prevent metallisation and therefore images could only be acquired when the process was not in the melting phase. Using a shorter wavelength camera also decreased the effect of emissivity on the measurements [8,9] compared to the longer wavelength technologies; resulting in a lower measurement uncertainty. This can be shown by calculating the percentage signal (DL) change per K change in temperature [10] using:

$$\%/K = 100 \times \frac{c_2}{\lambda T^2}$$

where c_2 is Planks second radiation constant 1.4388×10^{-2} m. K, T is the blackbody temperature in Kelvin and λ is the mean effective wavelength of the FPA. The %/K for typical infrared detectors are tabulated below for the standard preheat temperature of 1003 K. These calculations show that a small change in emissivity of, for example, 0.01 (1% of signal) will have a much greater effect on the measured temperature for the longer the wavelength detectors.

Wavelength (µm)	% Change in Signal per K	Error in K from emissivity incorrect by 0.01
1 (Silicon NIR)	1.43	0.70
4 (InSb MWIR)	0.36	2.78
10.75 (Microbolometer LWIR)	0.13	7.70

The vacuum chamber viewing port on the A2 was not located directly above the build plate, due to the position of the beam column, which resulted in the camera and lens being angled at approximately 20° from the build plate normal (Fig. 2). This allowed the entire build plate to be visible in-frame, with the focal point located at the centre of the build plate, at 400 mm working distance. The pixel radius on the imaging plane at the centre field of view was 66 µm, increasing to 79 µm at the maximum distance from the centre. The borescope design consisted of eleven lenses and a mirror, four of the lenses were custom designed (Fig. 3), with the remainder acquired from a catalogue supplier. The borescope had an f/# of 6 and a field of view covering 230 mm in diameter. The design consisted of an outer housing which held the lenses, with the lenses separated by sections of lens tube according to the spacing required by the design. The assembled borescope is shown in Fig. 4. A bandpass filter was fitted to the back of the borescope to define the wavelength range of the camera and to eliminate the majority of visible wavelengths (daylight) from reaching the FPA.

Filter selection was crucial to obtaining the temperature range and resolution required of the instrument. The planned temperature range for imaging with the instrument spanned from the standard preheat temperature of approximately 1003 K to the melting point of the

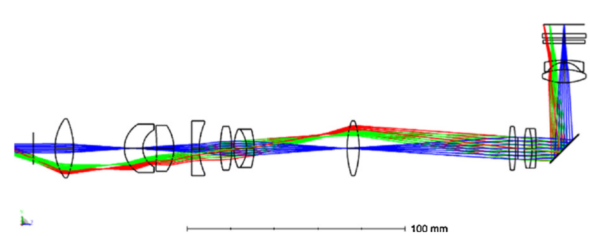

Fig. 3. Borescope lens design showing paths through the optical system (from the object plane on the left to image plane at the top) for on axis rays (blue), the maximum field of view (red) and $1/\sqrt{2}$ field of view (green) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).