ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-TUPP23

A BEAM DIAGNOSTICS SYSTEM OF ELECTRON BEAM MELTING FOR ADDITIVE MANUFACTURING*

R. Kavak†, E. Durna, M. G. Sanal, M. M. Sezer, ASELSAN A.S., Ankara, Turkey

Abstract

Electron beam melting has been used recently in additive manufacturing by various researchers. In those electron beam melting applications, the electron energy can be 60 to 100 keV, the beam current can be around 10 mA to 100 mA, and the beam spot size can be as small as 200 µm according to electron energy and beam current. Those parameters can result in very high beam power densities. The diagnostics of this powerful beam can be quite a problematic issue. As the electron beam current required for the application is quite similar to DC current, fast undestructive current measurement techniques for current beam profile and beam position are very limited in performance. Therefore, some destructive techniques to measure current and other beam properties are essential. As part of the beam diagnostics for electron beam melting application for additive manufacturing, the authors proposed a complete beam diagnostics system to measure the electron gun's capabilities and associate electromagnetic lens systems. The following properties have been diagnosed as part of this research work: i) Beam Current, ii) Beam Spot size for enlarged and focused beams, iii) Scanning velocity of the deflected beam, iv) Profile of the beam. The authors proposed methods to measure focused beam spot size and deflected beam scanning velocity using Secondary Emission Grid Sensors. Moreover, the authors proposed a new technique to measure beam profile using consecutively placed several copper plates with beam guiding holes of various diameters. The proposed beam profile measurement method effectively determines the useful beam radius for metal powder melting properties specifically to additive manufacturing applications.

INTRODUCTION

Recent advancements in engineering and material science require complex manufacturing processes [1]. For this reason, Additive Manufacturing (AM) challenges the traditional manufacturing methods in many cases [2]. According to the Additive Manufacturing Trend Report 2021 from HUBS, the global AM market grew 21 percent year-on-year to $12.6 bn in 2020. They also predicted that the AM market will be more than doubled, reaching $37.2 bn in 2026 [3]. The efficient usage of limited resources and the ability to produce complex shapes put AM forward when compared to traditional manufacturing [2, 4].

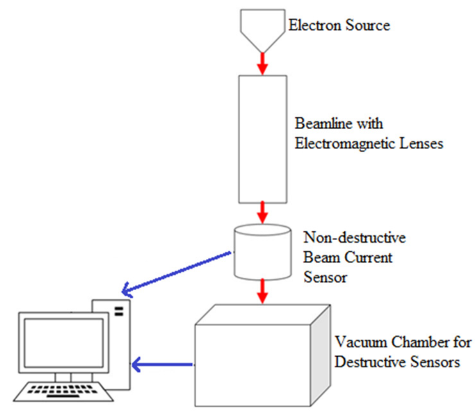


Figure 1: Overview of the EBM test setup and the proposed beam diagnostics system.

As the attention on AM has been dramatically increased among the researchers in the field, Electron Beam Melting (EBM) technique is getting used in the manufacturing process. EBM technique has been preferred to Selective Laser Melting (SLM) because of its advantages. One advantage is on that EBM provides higher beam power and beam scan velocity [5]. Another one is that EBM process occurs under a vacuum, but the SLM process works in an inert atmosphere. Therefore, oxidation of the parts is prevented in most cases for EBM [6].

An EBM system requires controlling several beam parameters in order to ensure the precision during manufacturing process. Some of them are beam power, beam spot size, beam scanning and jumping velocity [6]. The requirements of the EBM system are determined according to desired operating modes, and associated measurement mechanisms should be integrated to the calibration and test processes. Common EBM diagnostics methods are investigated in [7, 8].

In this paper, a beam diagnostics system is proposed for EBM process which diagnoses beam current, beam spot size for enlarged and focused beams, scanning velocity of the deflected beam, and profile of the beam. While proposed system makes use of SEM grid sensors to measure beam spot size and deflected beam scanning velocity, a novel method is put forward to measure the profile of the electron beam. Details of the EBM test system, and the proposed beam diagnostics system is described in the following sections.

SYSTEM DESCRIPTION

The EBM test system under investigation in this paper consists of three main parts, namely electron source, electromagnetic lenses, and test chamber. The source is where the electron beam is generated by Lanthanum Hexaboride (LaB_6) cathode at 60-100 kV. To manipulate the beam, sev-

* Work supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under grant number 3170014.
† rafetkavak@protonmail.com

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-TUPP23

eral electromagnetic lenses are used such as focusing, correction and deflection lenses, which are essential for AM process. Finally, the high-power electron beam hits to the target plate on the test chamber, on which selective metal powders can be used to conduct EBM experiments. The test setup system structure is as shown in Fig. 1.

The EBM test setup is formed such that used electron energy can be 60 to 100 keV, the beam current can be around 10 mA to 100 mA, and the beam spot size can be as small as 200 µm according to electron energy and beam current. Moreover, the beam position on the target plate which is located inside the vacuum chamber can be several tens of centimeters.

PROPOSED BEAM DIAGNOSTICS SYSTEM

The proposed beam diagnostic system, shown in Fig. 1, is intended to measure beam current, beam spot size for enlarged and focused beams, scanning velocity of the deflected beam, and beam profile, which are important specifically to electron beam melting for additive manufacturing. The destructive sensors are located in the vacuum chamber and non-destructive ones are on the beamline as shown in Fig. 1. In this part of the paper, measurements of intended beam properties are described in detail.

Beam Current Measurement

As the electron beam under investigation is a high energy one because of the requirements of additive manufacturing, the current should be measured via non-destructive means. The existing destructive current measurement techniques are either not standard products, hence expensive, or in a very high volume due to dissipated power.

The type of the current, on the other hand, should in a DC form because of the contour tracing, heating, and melting modes of operation of additive manufacturing. In these modes of operation, beam current is required to be constant. Mentioned requirements mandates the proposed beam diagnostic system to use non-destructive DC Current sensors with a microsecond grade fast response type. Authors propose using of DC Transformer type non-destructive current sensors [7, 8] for this purpose.

Beam Spot Size and Scanning Velocity Measurements

Beam spot size is one of most important properties of the electron beam which will precisely melt the metal powders on the target plate for additive manufacturing purposes. Different spot sizes show different melting behaviours with different times that the beam should be directed on to the unit length of metal powder. Besides, the spot size is intended to be kept as small as possible to ensure the precision on the additive manufacturing application.

The proposed beam diagnostic system is intended to measure the spot size of both focused and enlarged beams. When the beam is enlarged, the overall energy of the beam is distributed on a large area, which makes easier to detect the spot size. This enlarged beam spot size measurement can be used to calibrate the electromagnetic lenses along the beamline and to ensure the precise positioning of the beam on the target plate. This diagnostic system proposes the use of SEM Grid Sensors [7, 8], the manufactured grid sensor is as shown in Fig. 2.

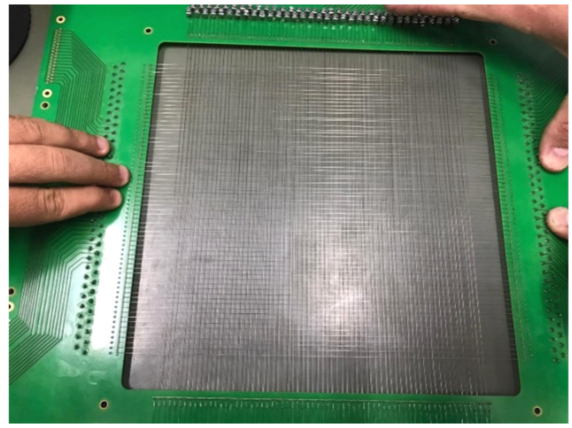


Figure 2: Manufactured SEM Grid Sensor.

On the other hand, the focused beam spot size should also be measured because of the earlier mentioned reasons dictated by additive manufacturing. As the energy density is extremely high, when the high energy electron beam is further focused, either the electron beam should not be directed on a measurement system for a long time, or the measurement system should be extremely large to handle high energy densities. To overcome the high energy density problem, a novel method is used to detect the focused beam spot size. The proposed method uses the SEM Grid readings by deflecting the electron beam as shown in Fig. 3. As shown in Fig. 3, the deflected electron beam passes through wires A and B, and blue and green waveforms are expected in the oscilloscope corresponding to wires A and B, respectively. The scanning velocity of the deflected beam can be measured by using the instants t_A and t_B that beam crosses wires A and B and the distance between them.

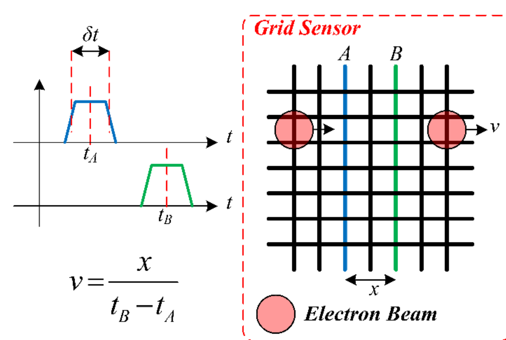


Figure 3: Proposed spot size and beam velocity estimation method using grid sensor.

Proposed Beam Profiler

The beam profiler is an important tool to assess the disturbance of electromagnetic lenses along the beamline. For this reason, a novel destructive beam profiler is proposed in this paper. As the energy is high, measurement of the

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-TUPP23

beam profile with destructive methods is not very easy. Therefore, beam is used in a pulsed mode and it is not focused. The proposed beam profiler is composed of stacked copper plates having openings with various radii on their center as illustrated in Fig. 4. These openings are stacked in a way that the largest opening is on top of all, and the others are put in a descending order in terms of their radii as shown in the top view illustration of the proposed beam profiler in Fig. 5.

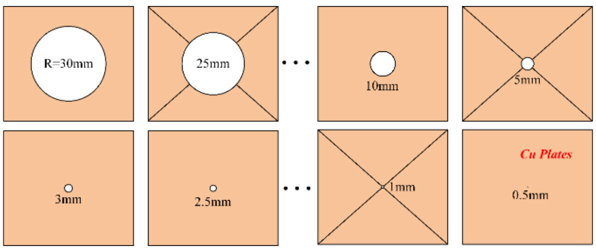


Figure 4: Copper plates of the proposed beam profile detector.

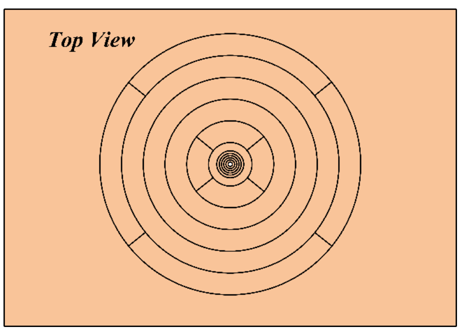


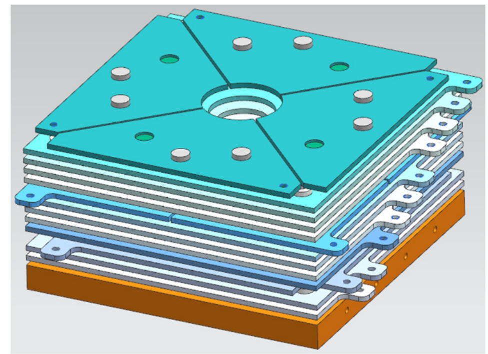
Figure 5: Top view of the proposed beam profile detector.

The proposed beam profiler should be precisely located to the beamline, and this is ensured by using the segmented plates in some layers. This is achieved by measuring the segment currents and making them equal, assuming the beam profile is symmetrical. The operation of the beam profile is such that as the beam hits towards the profiler, its portions smaller than the opening of a plate continue its way, while the others hit to the corresponding plate. The portion of the beam which hits to a plate is measured for each of the plates until the beam is finally hit to a dump plate at the bottom. The current densities are calculated by using the measured current and the corresponding effective area of each copper plate.

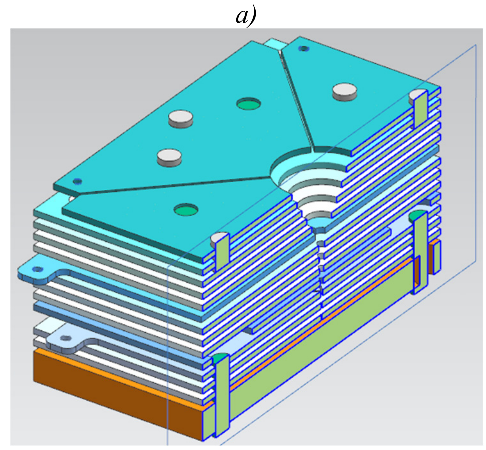
The proposed novel beam profiler is put forward first time in the literature and it is mechanically designed as shown in Fig. 6. The designed beam profiler is under manufacturing, only the analytical calculation results of expected beam profiler output is given in the results part of the paper.

Data Collection and Merging

The data which is produced by forementioned beam diagnostic sensors will be collected at a Central Control Unit. Those data will be evaluated, compared, and merged. The non-destructive current sensor will always be attached on top of vacuum chamber and will be sending data online. However, in addition to non-destructive current sensor, only one other sensor will be online since they are destructive/disturbing sensors by their structure and cannot be installed together. Hence all the data will be recorded and will be processed later offline.



a)



b)

Figure 6: Mechanical design of the proposed novel beam profiler a) isometric, and b) cross-sectional view.

The data coming from non-destructive current sensor and High Voltage Power Supply (HVPS) will be used as a feedback to monitor the beam current. The comparison of those two will also be used for the safety of the system. Considering that the electron beam is not hitting somewhere on the beamline, the current supplied from HVPS should be approximately equal to the current measured by the non-destructive current sensor which is at the end of the beamline.

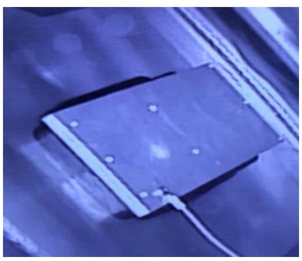
Offline comparisons and merging algorithms will be used to obtain more precise results. Beam spot size and beam profile for enlarged beams, or beam scan velocity for small angles are examples of those cases. The change at the beam quantities due to a change at system parameters can also be measured with different sensors, recorded, postprocessed offline and merged.

RESULTS

Some parts of the proposed beam diagnostics system are already integrated to the electron beam additive manufacturing test setup, while some others are still in manufacturing or testing phase. For this reason, initial tests are performed only with current measurements, while beam profiler outputs are given as analytical calculations for a syn-

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-TUPP23

thetic electron beam. The electron beam additive manufacturing test setup is operated to measure the DC current waveforms and it is shown that the readings of the DC current sensor is in a close correlation with the HVPS current output, as expected. Figure 7 shows the interior camera view of the vacuum chamber while electron beam hits a dummy victim copper plate during current measurements and electron gun characterizations.


a)

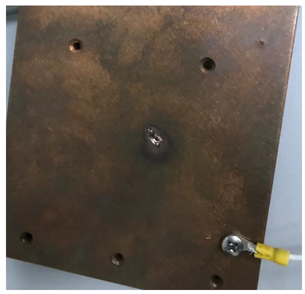
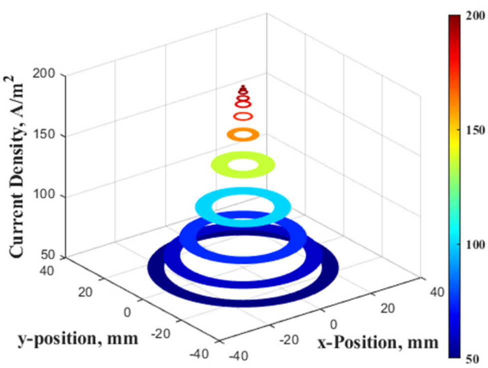
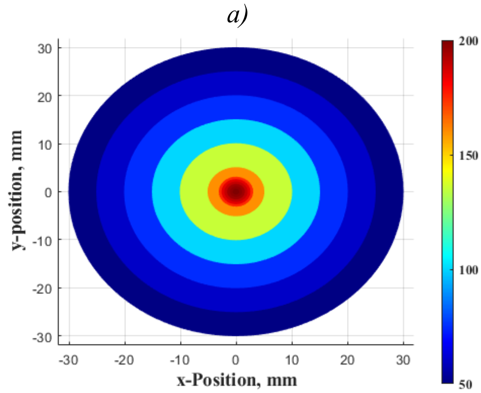

b)

Figure 7: Images showing the a) camera recording during experiments on a dummy victim plate, and b) the victim plate after experiments.



a)



b)

Figure 8: Analytical results of the expected performance for the proposed beam profiler a) 3D view, and b) top view.

As the novel beam profiler proposed in this paper is still under manufacturing, only its theoretical results considering the analytical calculations is illustrated. As the currents that hit to the effective area of each copper plate is measured, its corresponding current density should be calculated by dividing the current value by the area of the effective ring surface that faces the electron beam. Then each of the current densities for corresponding ring areas should be drawn in a 3D graph as illustrated in Fig. 8. The results shown in Fig. 8 is deduced using a synthetic electron beam. The form of the result graph of the beam profiler is in a close correlation with the synthetic electron beam profile. The expected calculations give a hint that the proposed beam profiler is very effective for diagnosing the beam profile of symmetrical electron beams.

CONCLUSION

In this paper, a beam diagnostics system is proposed for EBM process which diagnoses beam current, beam spot size for enlarged and focused beams, scanning velocity of the deflected beam, and profile of the beam. While proposed system makes use of SEM grid sensors to measure beam spot size and deflected beam scanning velocity, a novel method is put forward to measure the profile of the electron beam. As the functional tests of the proposed beam diagnostics system are still in progress, only the initial dummy victim plate tests and analytical results are included in this paper. Nevertheless, the findings of the analytical results show that the novel beam profiler device along with the other components of the beam diagnostics system is a complete tool collect, merge, and evaluate the required data in order to ensure precision in AM processes and provide emergency protection and calibration of electromagnetic lens system along the beamline.

REFERENCES

[1] O. Abdulhameed, A. Al-Ahmari, W. Ameen, and S. H. Mian, "Additive manufacturing: Challenges, trends, and applications", *Advances in Mechanical Engineering*, vol. 11, no. 2, p. 168781401882288, Feb. 2019. doi:10.1177/1687814018822880

[2] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing", *Business Horizons*, vol. 60, no. 5, pp. 677–688, Sep. 2017. doi:10.1016/j.bushor.2017.05.011

[3] Additive manufacturing trend report 2021, https://www.hubs.com/get/trends/.

[4] H. Paris, H. Mokhtarian, E. Coatanéa, M. Museau, and I. F. Ituarte, "Comparative environmental impacts of additive and subtractive manufacturing technologies", *CIRP Annals*, vol. 65, no. 1, pp. 29–32, 2016. doi:10.1016/j.cirp.2016.04.036

[5] B. Wysocki, P. Maj, R. Sitek, J. Buhagiar, K. Kurzydłowski, and W. Święszkowski, "Laser and Electron Beam Additive Manufacturing Methods of Fabricating Titanium Bone Implants", *Applied Sciences*, vol. 7, no. 7, p. 657, Jun. 2017. doi:10.3390/app7070657

[6] P. K. Gokuldoss, S. Kolla, and J. Eckert, "Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines", *Materials*, vol. 10, no. 6, p. 672, Jun. 2017. doi:10.3390/ma10060672

[7] P. Strehl, *Beam Instrumentation and Diagnostics*. Springer, 2006.

[8] P. Forck, *Lectures Notes on Beam Instrumentation and Diagnostics*. (GSI, Darmstadt, Germany) Joint University Accelerator School, January-March 2017.