ACQUISITION OF REAL-TIME OPERATION ANALYTICS FOR AN AUTOMATED SERIAL-SECTIONING SYSTEM

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ABSTRACT

Mechanical serial sectioning is a highly repetitive technique employed in metallography for the rendering of three-dimensional reconstructions of microstructure. While alternate techniques such as ultrasonic detection and micro-computed tomography have progressed much in recent years, few alternatives provide equivalent opportunities for comparatively high resolutions over significantly-sized cross-sectional areas and volumes. To that end, the introduction of automated serial sectioning systems has greatly heightened repeatability and increased data collection rates while diminishing opportunity for mishandling and other user-introduced errors. Unfortunately, even among current, state-of-the-art automated serial sectioning systems, challenges in data collection have not been fully eradicated. Therefore, this paper highlights a newly developed and readily deployable interface providing real-time monitoring of material removal rates as well as tools for identifying interruptions or anomalies in data collection in conjunction with an automated serial-sectioning system.

Outline

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   b. Development of automated serial sectioning systems
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III. Data Collection Monitor
   a. Software Components
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IV. Discussion & Conclusions
   a. Thoughts on Close-Loop Feedback
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I. Introduction

The earliest example of serial sectioning in materials science dates back to the early 1900's with the work of Otto Forsman's investigation of ferrous pearlite [1]. Decades later in 1962, Hillert used serial sectioning to evaluate the shape of pearlitic ferrite in steel [2] while Caron applied the technique to better understand the shapes and sizes of grains in a titanium alloy in a thesis dissertation in 1970 [3]. However in 1991, the application and occurrences of mechanical serial sectioning within the materials science literature increased dramatically beginning with the work of Hull and co-workers [4] and continuing on with the efforts of Mangan and Shiflet [5,6], Kral and Spanos [7-10] and Voorhees and co-workers [11-15]. One chief significance of each of the aforementioned efforts has been each work's contribution to the field in advancing the methods of data collection or the processes used for reconstruction of mechanical serial sectioning data.

One such advance was the introduction of the first fully automated serial sectioning system by Alkemper and Voorhees [13]. The system combined a diamond blade micro-miller, micron-sensitive three-axis stage and a linear variable differential transformer for alignment, registration and depth measurement. While the first of its kind, its applications were largely focused on relatively "soft" metallic systems such as Al-Cu and Pb-Sn. Spowart and Mullens later developed an automated approach to serial sectioning by combining a 6-axis robotic arm, an inverted microscope, an ultrasonic bath and a polishing wheel with interchangeable diamond abrasive films [16-18]. UES, Inc. later purchased the rights to license this tool, commercialized the unit and have deployed units worldwide [19]. In 2012 an alternative automated serial sectioning system, Genus_3D™ was reported by Adachi et al. [20], however very little is available in the literature, at this time, regarding this system.

The following tools presented in this paper are generally adaptable to any mechanical serial sectioning data set provided a specific ordering of data is available. The authors have procured a RoboMET.3D™ for three-dimensional microstructural investigations, therefore, the tools presented in this paper will be presented with the RoboMET.3 D™ as context.

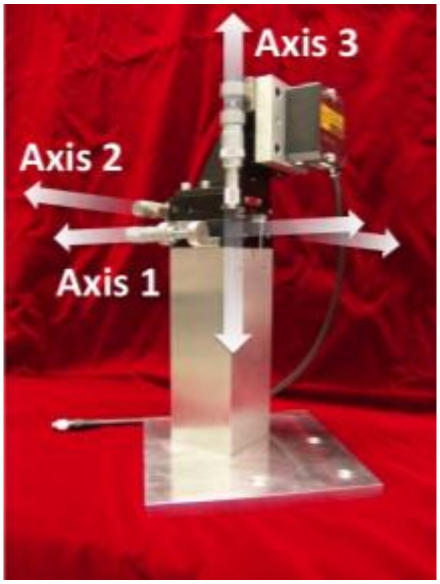
In its basic configuration, the RoboMET.3D™ version 2, combines and integrates a motorized metallographic polisher, a dual ultrasonic bath, a ZEISS™ inverted microscope and at least one multi-axis robotic arm for translation of a single mounted sample through each of the aforementioned stations for metallographic preparation [21]. The entire system in located within a windowed enclosure to allow safe autonomous operation following the input of a user defined preparation routine. The user also specifies the number of cycles the routine is to be executed. Sandia National Laboratories' RoboMET.3D™ is shown in Figure 1. While autonomous and continuous operation for hours is typical, little is offered in terms of user feedback should an anomaly occur with respect to the sample or should an interruption occur with respect to the system. Either instance can presumably lead to damaged samples, lengthened data collection times and in some cases, unnecessary use of metallographic preparation consumables. Additionally, the system's primary method for measuring removal rate is based on the average focus height for each slice which can be problematic if image quality is inconsistent or the cross-sectional area of the region of interest is not uniform throughout the experiment. As such, the tools presented in this paper provide alternative means to mitigate these challenges within automated serial sectioning systems as well as provide the user a richer, real-time context during data collection.

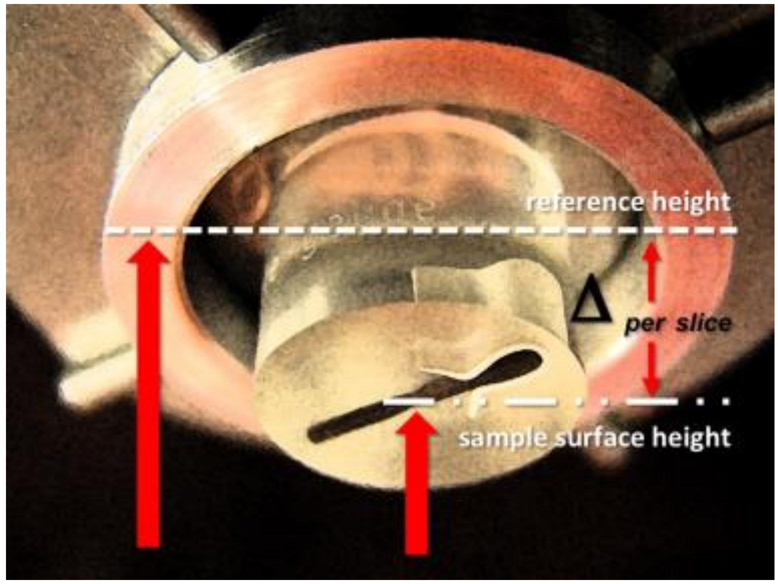
Figure 1 - RoboMET.3D at Sandia National Laboratories, Albuquerque NM

II. Non-Contact Material Removal Measure

By design, the RoboMET.3D™ system uses a per slice average auto-focus height to approximate material removal rates throughout a serial sectioning experiment. This method is generally acceptable provided the sample being interrogated maintains a uniform cross-sectional area throughout the process and image quality in each slice is relatively similar. For cases in which a full silhouette boundary contained within the serial-sectioned image changes in size, this subtlety can make a profound difference in the estimated removal rate, thereby adversely biasing the measurement and often resulting in an inaccurate value. For example, when the surface area becomes larger in subsequent slices, the estimated removal rate proposed by the average auto-focus can in fact provide a negative removal rate. To address this problem and provide a secondary measure with added fidelity, a laser has been integrated into the system, operating along the robotic arm's arc of travel, to provide a measure that is insensitive to changes in the cross-sectional area of a sample.

A KEYENCE™ laser interferometer system using a LKH057 sensor head was incorporated into the RoboMET.3D enclosure via a custom three-axis, micron-resolution stand, as shown in Figure 2a. The measurement is based on the difference between an unchanging reference height relative to the sample holder and the height of the sample surface which constantly recedes throughout the serial sectioning experiment (Figure 2b). The method requires no physical contact with the specimen and is repeatable to within a few microns. The sensor head itself has a measurement range of 50 ± 10 mm and is interchangeable with other KEYENCE™ sensor heads having varied ranges and resolutions [22]. A schematic of the three-axis mount with laser positioned below a sample within the RoboMET.3D™ is shown in Figure 3.





(a) (b)

Figure 2 - (a) Three-axis stage mount for laser interferometer (b) schematic of measurement differential between reference height and sample surface

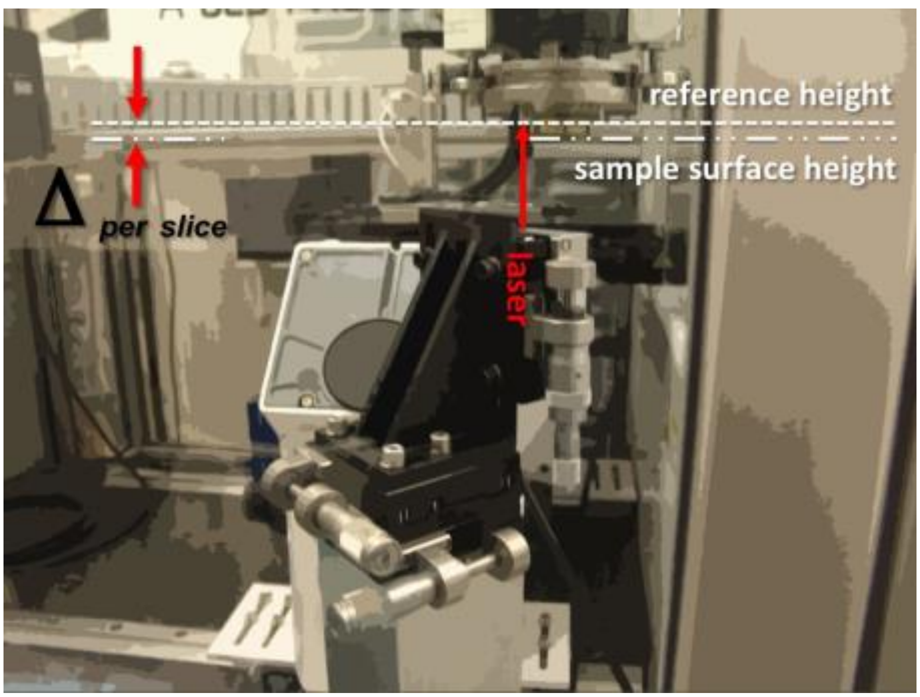
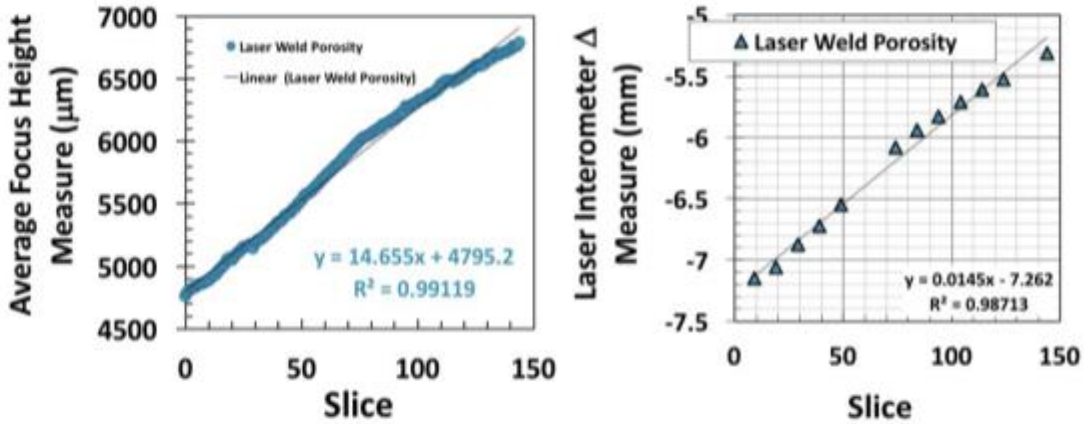
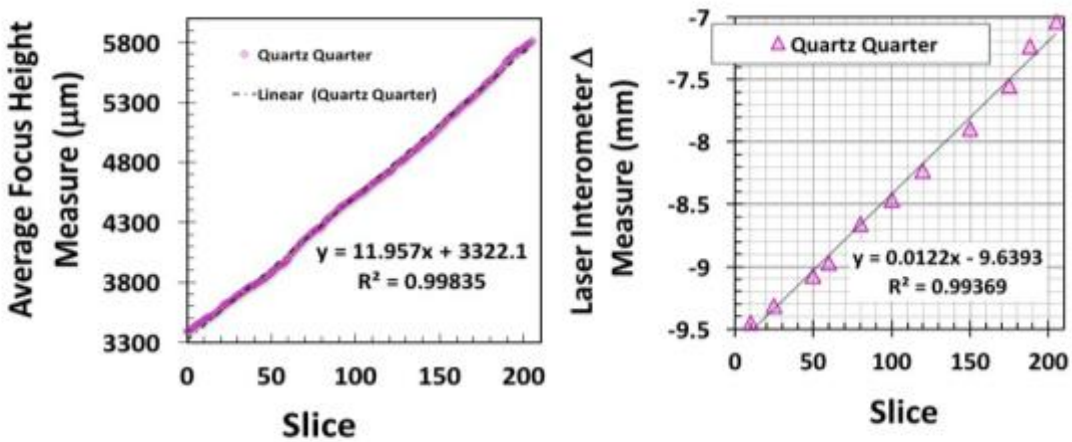


Figure 3 - Laser measure assembly, sample and sample mount within the RoboMET.3D enclosure

To demonstrate the validity of the technique, a series of control experiments were performed in which the cross-sectional area of the sample was maintained throughout serial sectioning. Multiple series of intermittent, independent laser measurements compared well against the system's conventional measure across a variety of material systems. See Figure 4.



(a)



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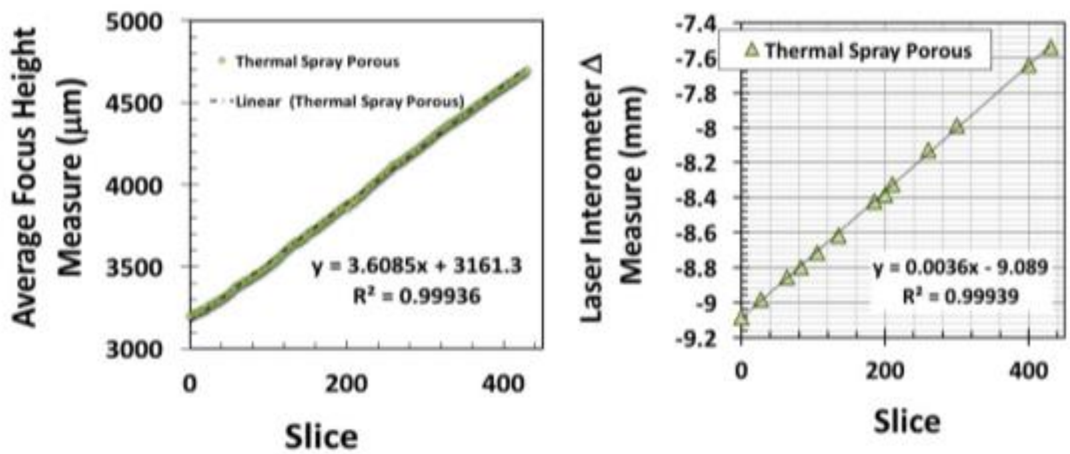
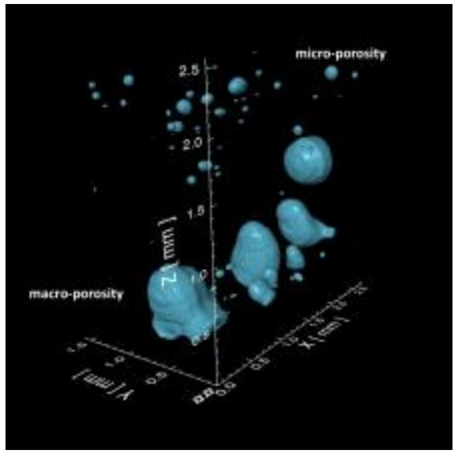


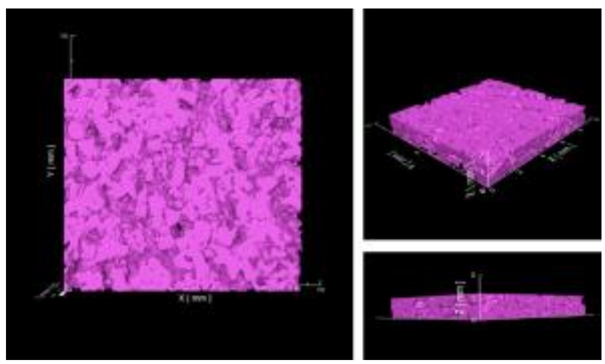
(c)

Figure 4 - Serial sectioning material removal rates measured by average focus height and confirmed by non-contact laser measure for (a) porosity in laser welds of 304L stainless steel (b) geological formations of sandstone and (c) thermal spray coating on a substrate of stainless steel.

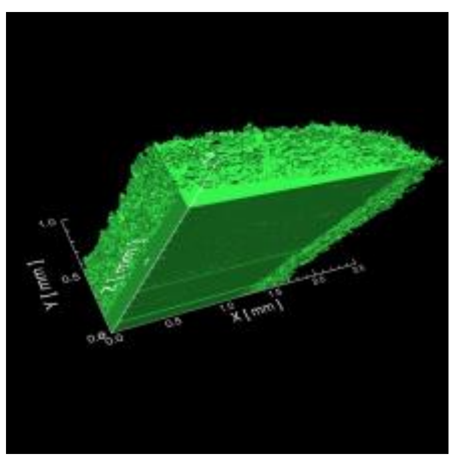
As a reference, the three-dimensional reconstructions from the data acquisitions denoted in Figure 4 are shown here in Figure 5.



(a)



(b)



(c)

Figure 5 - 2D optical micrographs and accompanying 3D reconstruction of (a) laser weld porosity in a stainless steel, (b) sandstone grains in a geological formation and (c) thermal spray coating of 304L stainless steel on a stainless steel substrate

III. Data Collection Monitor

Autonomous operation of any metallographic serial sectioning system is paramount to its benefit. As such, the performance of automated serial sectioning systems are chiefly accompanied by an expectation of lengthy and unsupervised operation. To increase efficiency during user absence, a set of software tools have been developed to provide real-time tracking of data acquisition, operational cycle times as well electronic user notifications in the event of an unintended system error or pause.
Using LabVIEW™, an extensible, graphical user interface with multiple panes was created for visualization of the aforementioned items through appropriation of the RoboMET.3D generated text data files. In this regard, the input data source is flexible. The tools described below simply require parsable text data that describe the serial sectioning experiment with the expectation of a certain ordering of data attributes per slice. (As this data input can quite presumably be produced from a variety of sources, a complete list of these attributes and their anticipated ordering as utilized in this application are included in the "help" files of the software.) The main tab of the graphical user interface, which is called the Mechanical Serial-Sectioning Data Assistant© (or MECH-SSDA©) provides a real-time visual of the material removal rates acquired by both the average montage focus height as well as the laser interferometer, as often as new data is collected for either. See Figure 6.

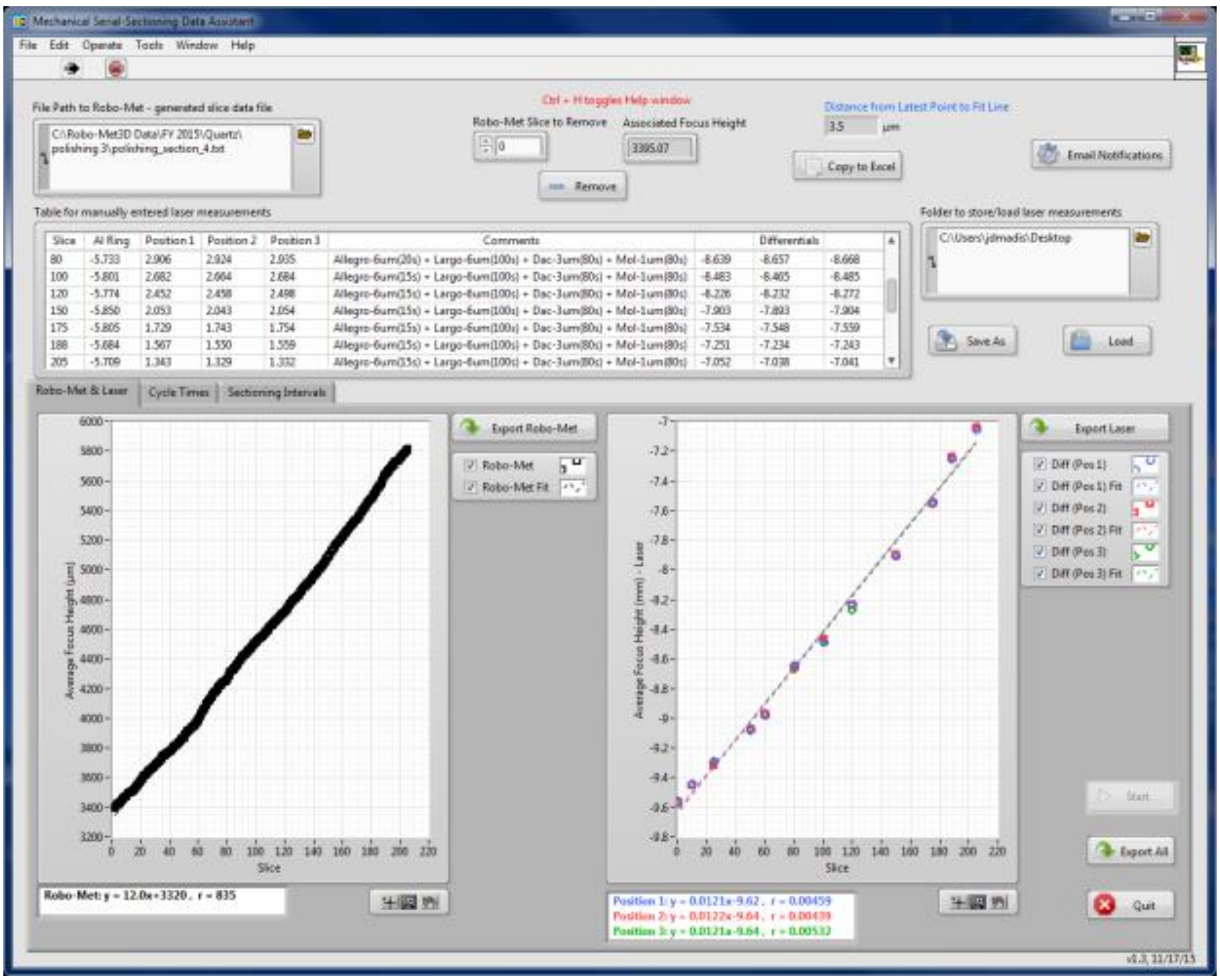


Figure 6 – Pane 1 of the MECHSSDA, Pane 1 showing (2) independent removal rate measures

Furthermore, since most automated serial sectioning systems can be generally divided into two primary steps, polishing and imaging, the second tab of MECH-SSDA© provides a quantitative monitoring of cycle times associated with each polishing and each imaging interval, independently. While polishing and imaging data are recorded for every slice, the collective aggregate of cycles times are provided by histogram to allow a user to quickly determine the relative frequency and the global distributions of cycle times specifically associated with either polishing or imaging as shown in Figure 7.

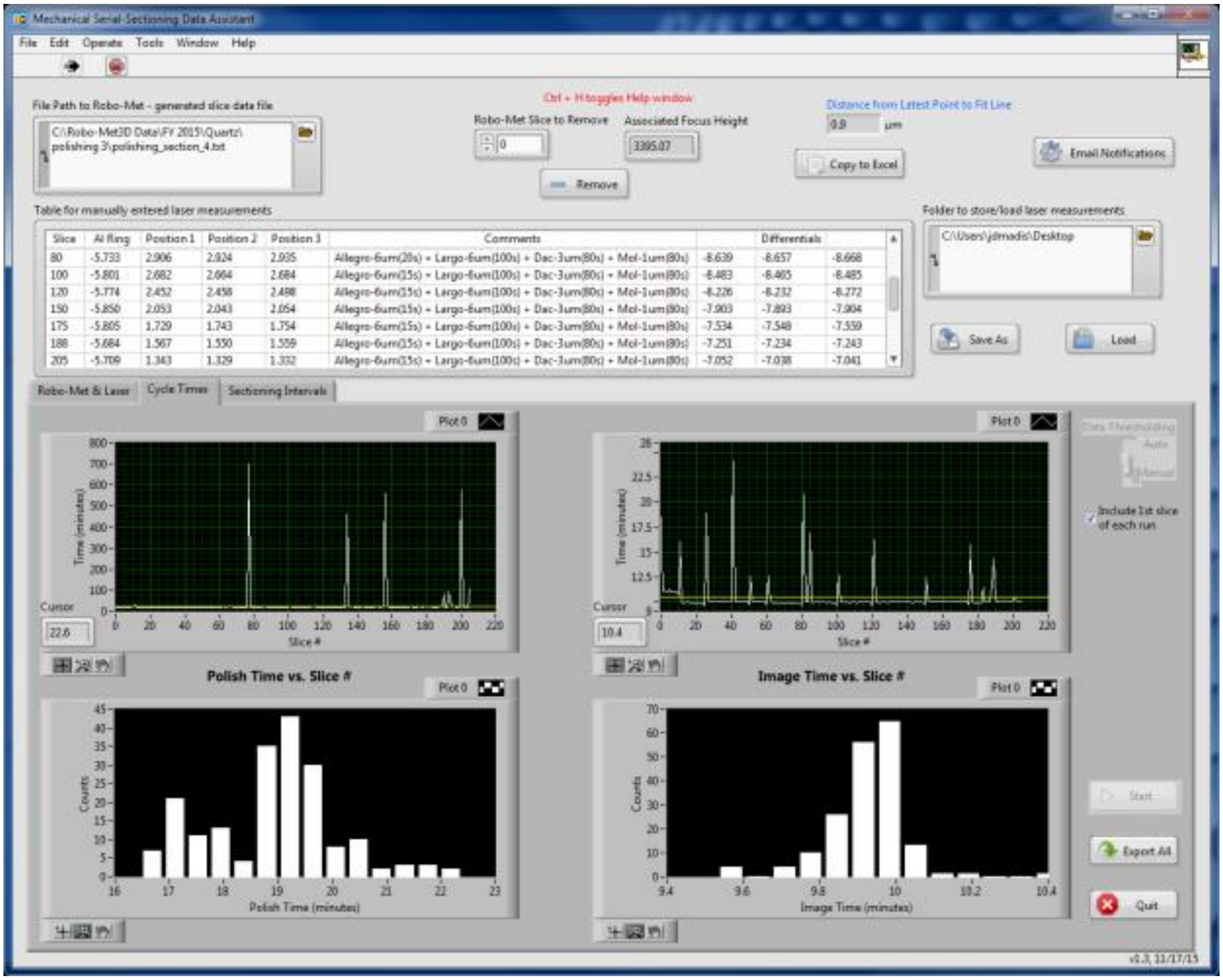


Figure 7 - Pane 2 of the MECHSSDA user interface showing cycle times as a function of slice number for polishing and imaging

The third tab provides an aggregate view of the temporal footprint of the entire serial sectioning experiment as a function of serial-sections (or "slices") acquired. Here, in addition to the total experiment time expended, the user is afforded an immediate and visually identifiable measure of the time expended for the collection of each slice within the overall experiment, See Figure 8. Most plots within panes 2 and 3 of MECH-SSDA illustrate a measured quantity as a function of slice number so a slice by slice behavior can be readily ad rapidly surmised visually. As can be observed, the peaks within the polishing time plots (see Figure 7) and the discontinuities within the total run time plot (see Figure 8) correspond directly for given outliers according to their slice number. These instances denote lengthy pauses in system operation due to the completion of a set during an over-night run prior to continued operation of the system during the next work day. Additionally, within the lower sections of panes 2 and 3, all data are also plotted as real-time histograms which can be adjusted by clicking and dragging up or down on the yellow line appearing within the plot to eliminate outlier data points or zoom in on specific portions of the data thereby identifying the most frequently recurring time intervals or range of intervals for a given action.

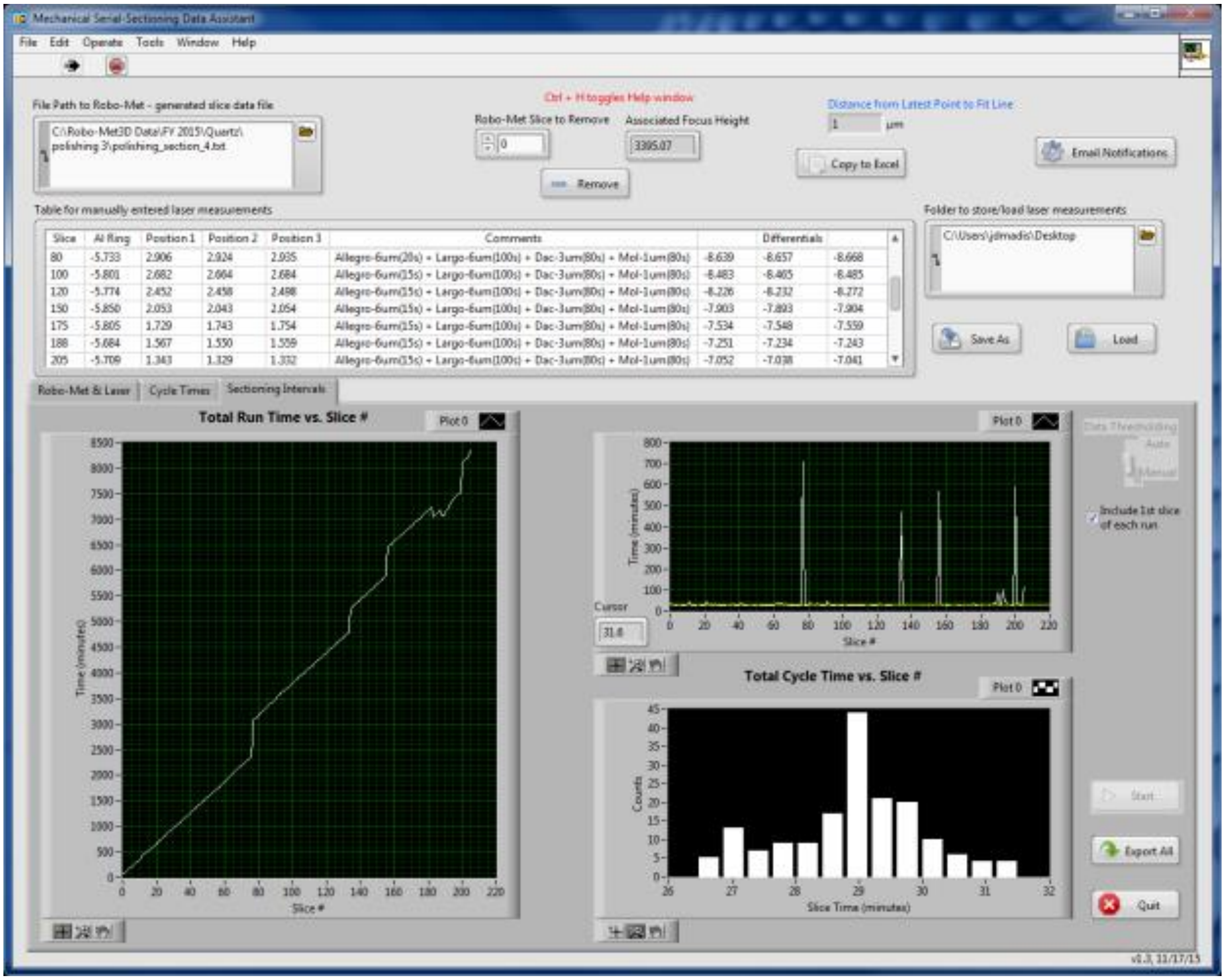


Figure 8 - Pane 3 of the MECHSSDA user interface showing aggregate data collection time and total cycle times for each serial-section collected

Lastly, using a variety of criteria readily quantifiable from the acquired data, MECH-SSDA© can also send any number of users an email should certain events present themselves. A listing of the selectable events currently available in version 1.3 of MECH-SSDA© are shown in Table 1.

Table 1 - Current Electronic User Messaging Options

Event	Customizable Criteria	Argument or Units
Abnormal Material Removal Rate	+/- Deviation from Average	Microns
System Errors	Exclude errors of insignificance	Error Code Numbers
Log File Error	Disregard known log abnormalities external to system operation	Log Index Values
Completion of Experiment	--	--

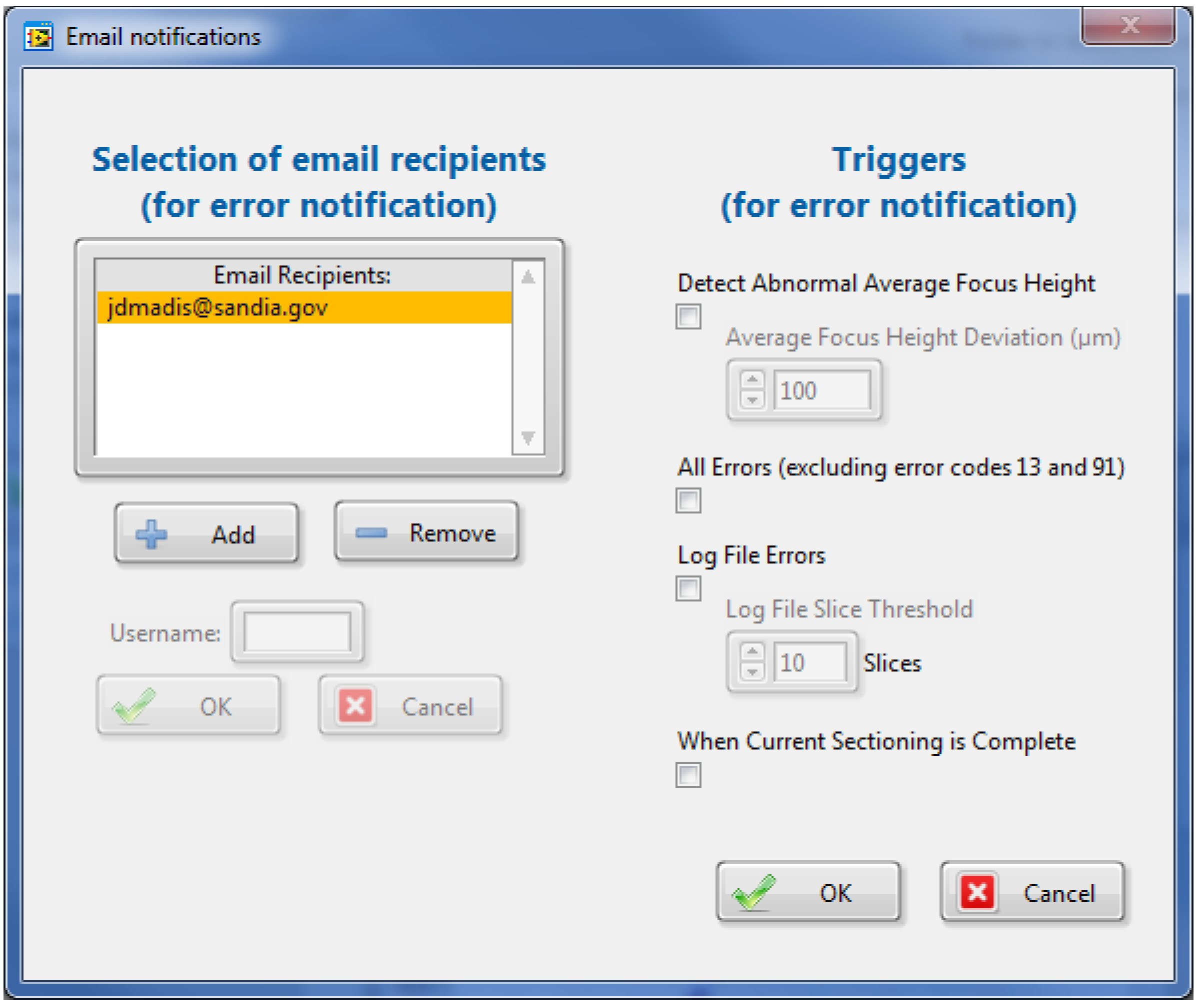


Figure 9 - Interface showing error notification setup

IV. Discussion

Automated serial sectioning systems present a definite advance in metallographic preparation toward three-dimensional interrogations of microstructure. However, due to the lengthy and often costly investment required for data collection, tools yielding rapid, real-time assessment of data provides a number of potential advantages. The benefits of the MECH-SSDA© tool presented here is at-least three-fold. First, since automated serial-sectioning systems, by design, operate unattended for a significant portion of time, the data tracked helps provide the user a detailed picture of system operation while unattended, for rapid identification of any abnormalities should an unintended event occur during user absence. Second, the data tracked provides the user an empirical method to more reliably and more readily forecast operation time toward experiment completion. With little additional effort, this forecasting can be extended to consumables used (e.g. SiC paper, diamond suspension, abrasive extender, etc.), computer memory to be occupied by the dataset, as well as operational ratios for system usage vs. periods of non-use. Lastly, this real-time data collection footprint is useful toward enabling the more ambitious goal of meaningful and robust closed-loop operation.

Closed-loop control in automated serial-sectioning systems would provide for intelligent correction of the system without user intervention. However, for this to be possible, real-time assessment of data acquisition compared to some standard would certainly be required. As such, the MECH-SSDA© tool and any others of its kind provide a useful initial step toward the eventual development of closed-loop operation in automated serial sectioning systems.

V. Conclusions

Customizations to assist in the operation of an automated serial sectioning system have been presented. These customizations include a non-contact method to assess material removal rates and a real-time operational data collection analyzer called MECH-SSDA©. The non-contact material removal assessment is obtainable over a range of 50 mm with a resolution on the order of microns. The real-time data collection analyzer is both deployable and extensible and has been implemented in conjunction with a RoboMET.3D™ version 2 automated serial sectioning system. The data analysis tool tracks two separate and independent measures of material removal, polishing and imaging cycle times as well as total run times. While only an initial release, MECH-SSDA© represents a very useful step toward the development of a tractable closed-loop integration based on quantifiable metrics of real-time data collection for automated mechanical serial sectioning systems. If you have an interest in acquiring an executable of the MECH-SSDA© software, please contact the authors at jdmadis@sandia.gov or gpoult@sandia.gov.

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