MATLAB-based Analysis of Micro-target Surfaces for Evaluation and Optimal Laser Shot Positioning

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Introduction

This report describes the development of a set of MATLAB scripts to assist in the characterisation of targets for delivery in a high-power laser experiment carried out on the Gemini laser at the Central Laser Facility.

The motivation behind the project is to provide an estimate of the best location in the XZ plane for a laser shot incident on the edge of metal foil targets mounted on a 4x4 array and, more generally, to evaluate the experimental value of each target, i.e. how closely it conforms to the experimental specifications.

Background and Aim

The experiment proposed to investigate proton acceleration via surface wave excitation at parallel and grazing incidence on the Gemini laser. This involved shooting a laser along the surface of a metal target ranging in thickness from 1-25um. The targets were sufficiently small that idealised assembly was very challenging. The targets were not perfectly flat, unwarped or free from surface damage and the requirement for laser machining resulted in various surface and edge defects which needed characterisation.

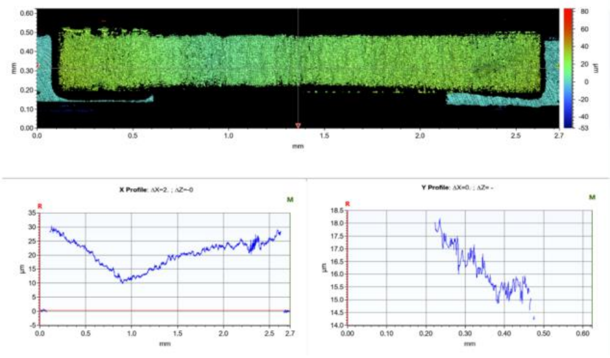

Figure 1: *A white-light interferometry scan along the top surface of a target foil*

The aim of this project was to collect interferometry data from the surface of each target foil and to write an algorithm to analyse to estimate the location horizontally of the foil's least warped point along the z-axis, as seen looking at the thin edge. Figure 1 shows an interferometry scan using a Bruker ContourX displayed on its integrated Vision64 software. The laser axis is a vertical line in the upper image of Figure 1 and its lineout is given by the lower-right graph.

Figure 2 shows the 4×4 array upon which thin gold micro-foil targets were mounted at 45 degrees with respect to the plane of the array.

Practical Challenges

The interferometer data was challenging to obtain because the foil must sit quasi-normal to the optical axis of the interferometer which proved difficult due to the foil being mounted at 45 degrees with respect to the face of the array. The scanner head was difficult to position for the lower rows of targets without physically clipping them due to the short working range of the objectives. Various iterations of target array holders were designed and 3D-printed to work around this issue. Eventually it was found that all of the scans could be successfully performed if a physically smaller objective lens was used (coincidentally with a higher magnification) and if the interferometer stage was tilted and post-corrected.

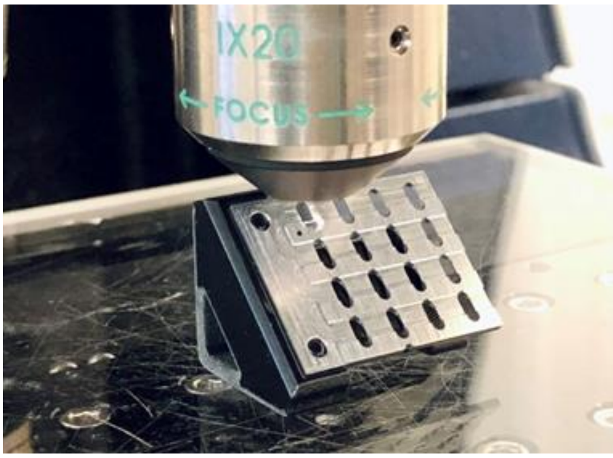

Figure 2: *4x4 target array holding target foils at a 45 degree angle with respect to the plane of the mount*

The Algorithm

Because the laser spot is not infinitesimally small each possible 'least warped' section of the foil is allocated a particular width of n data points.

The chosen method for finding the least warped of the possible sections is a simple search with time complexity of $O(m \cdot n)$, where m is the total number of data rows searched and n is the width of the laser spot in data points. For time efficiency the 'warp indicator' statistic (defined in the next paragraph) for each data row is calculated and stored in an array before the search begins thus the memory complexity is of $O(m)$.

The chosen metric by which to evaluate the foil warp or surface imperfection of a given data column here is called a 'warp indicator'. A few different warp indicators have been tested including simply measuring the range $(\max(array) - \min(array))$ or using the gradient of the best fit line for each data column. These metrics are crude and only give an indication of the absolute warp: for example, deformation compared to a smooth flat surface with a gradient of zero.

Because the target array positioning wheel used on-experiment can be rotated to any given angle the relative warp is a more important criterion (as any angular offset can be corrected by the wheel). Therefore, a much more useful warp indicator is the coefficient of determination (or R^2) value of the best fit line corresponding to a given data column. This is a measure of how closely the data conforms to the line which works quite well for the purpose of estimating relative warp and surface height uniformity. The gradient of this best fit line is then used to determine the correction angle in degrees of the target array holder wheel which is then output by the script and issued to the users upon characterisation and delivery of each target mount.

The Use of R^2 Values

As mentioned above the coefficient of determination (R^2 value) of a best fit line is a measure of how closely data conforms to the line.

In the context of this investigation there are two main reasons why the data for a given foil might not conform well to the best fit line. Firstly the foil's surface profile may have a curved rather than linear form, though this has a comparatively small effect because these foils tend to twist with a low or negligible degree of curvature. Secondly there may be noise in the foil's surface potentially caused by laser machining errors, high surface roughness, small surface contaminants or optical measurement artefacts from the interferometer caused by steep wall angles. The R^2 value is unaffected by noise or wrinkles aligned with the laser axis because this is parallel with the data slices/columns taken along the array.

The outcome is that as well as R^2 values being used to evaluate the ideal location for the laser focal spot (in the x-axis) for a given foil, the average R^2 value of this chosen location can also be used to get a rough overall measurement of the experimental value of a given foil. A low average R^2 value could be the result of imperfections either physically or in the interferometry scan both of which are factors that would make a given foil less useful to an experiment.

The main caveat with using R^2 values for evaluation is that the values are near to meaningless if there is insufficient data which can occur if there is insufficient lighting on the foil surface or the sample is out of the measurement range during the interferometry scan. Therefore the main function script (LeastWarpedSection.m) was modified to return NaN (Not a Number) output data if the number of data points between the reference lines was below a certain threshold and it advised that the target should be avoided as out of specification.

Evaluation of Characterised Targets

Using a new script all of the characterised target data can be passed to the LeastWarpedSection( ) function and the output data can be saved and plotted.

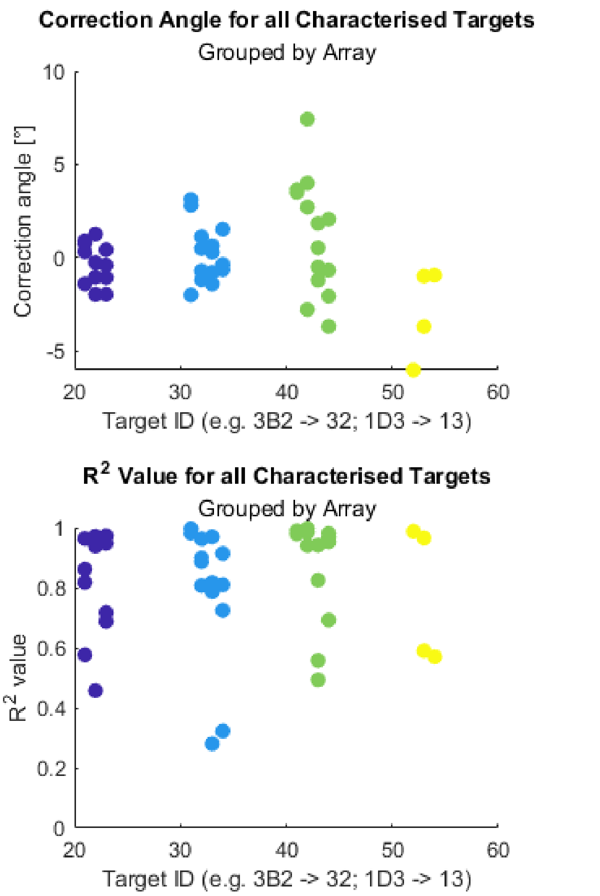

Figure 3: *(Upper): Pitch correction angle output by the code from the interferometer data. (Lower): R^2 value output for each target foil. (Colour grouped by array.)*

Figure 3 shows plots of the output data coloured by target array. The x-axis 'Target ID' refers to a simple non-unique identifier for ease of plotting for this report. Each target foil is given a unique foil reference identifier which is issued to the users on target delivery.

Errors and Assumptions

It is assumed generally that the foil has a constant thickness such that the bottom surface lies a constant height offset below the scanned top surface. This is not necessarily true, however, the warping of the foil caused by mounting issues is a much larger source of error than the small variation in foil thickness from a sample.

The interferometer is liable to occasionally produce erroneous or unexpected readings due to optical effects, or even microscopic contaminants on the target surface. Such readings are unlikely to significantly affect the result produced by the algorithm since even if they are within the search bounds, they are filtered out by the both the interferometer and best fit line code.

Notes on the Project

Unexpectedly the most time-consuming part of this project was trying to read a MATLAB array from the native surface roughness output files from the interferometer (.OPD or .OPDx). The script originally written by Bruker was outdated and required significant refactoring and bug-fixing.

Resulting Scripts

The project was made available to the users via a public repository on GitHub which included documentation on installation and use of the project. The interferometry data was uploaded to a repository for the user group who were then responsible for running the script when needed.

The main script, when run, displays a 2D surface colour plot of the target foil corresponding with the chosen data file. The surface plot is annotated with lines representing the reference bounds, search bounds, and resulting least warped section. The axes of the graph are all scaled in microns. Figure 4 shows an example plot of target cell A2 of the third target array delivered for the experiment, denoted as “3A2”.

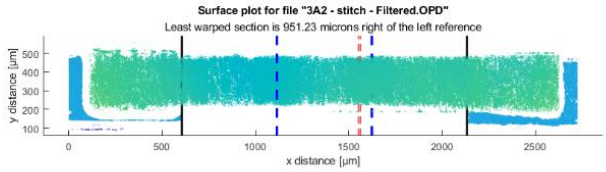

Figure 4: *Surface plot, reference/search bounds and least warped section output from the MATLAB code.*

The position of the calculated least warped section relative to the left reference bound is displayed on the graph as a subtitle. This allows the user group to move to a precise location from a referenced location to ensure that the laser is focused on the least warped section of the foil. It is also printed into the command window along with other metrics such as the required target array wheel correction angle and height range along the lineout.

Conclusions

The fabrication of micro-target arrays such as those used in this experiment is a significant challenge and, as a result, the foil is never completely perfect. Consequently it is important to evaluate each target to maximise its usefulness and to take its imperfections into account.

Such evaluation was made possible through this project and it proved to be very useful for the experiment. This is a capability which could be adapted to highlight specific areas on the target foil of low surface roughness, for example, which may be useful for typical high-power laser experiments shooting at target-normal incidence. Developing it made use of a practical workflow for analysis of interferometry data in MATLAB.

Acknowledgements

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