Enhanced Dual Confocal Measurement System

K. Tomlinson,[1] C. T. Seagle,[2] H. Huang,[1] G. E. Smith,[1] J. L. Taylor,[1] R.R. Paguio,[1]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608*
[2]*Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1168*

Contact: Kurt Tomlinson

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
505-284-1350 (Phone)
ktomlin@sandia.gov

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A measurement instrument utilizing dual, chromatic, confocal, distance sensors has been jointly developed by General Atomics (GA) and Sandia National Laboratories (SNL) for thickness and flatness measurement of target components used in dynamic materials properties (DMP) experiments on the SNL Z-Machine (Z). Compared to previous methods used in production of these types of targets, the tool saves time and yields a 4x reduction in thickness uncertainty which is one of the largest sources of error in equation of state (EOS) measurements critical to supporting the NNSA's Stockpile Stewardship program and computer modeling of high energy density experiments. It has numerous differences from earlier instruments operating on the dual confocal sensor principle to accommodate DMP components including larger lateral travel, longer working distance, ability to measure flatness in addition to thickness, built-in thickness calibration standards for quickly checking calibration before and after each measurement, and streamlined operation. Thickness and flatness of 0.2mm-3.3mm thick sections of diamond machined copper and aluminum can be measured to "sub-micron" accuracy. Sections up to 6mm thick can be measured with as-yet undermined accuracy. Samples must have one surface which is flat to within 300µm, lateral dimensions of no more than 50mm x 50mm, and height less than 40mm.

I. INTRODUCTION

Experiments conducted on Z to determine material properties at extreme temperatures and pressures often use targets containing nominally flat components made of rigid materials.[1] Accurate measurement of component thickness and flatness is crucial to reducing uncertainties in the analysis of dynamic compression data. For shock compression experiments, an uncertainty of even 10μm in a thickness can lead to a calculated shock velocity uncertainty of greater than 10%.[2-3] In shockless compression experiments to determine equations of state and strength, sample thicknesses are used in combination with velocimetry to determine sound velocities.[4] Uncertainties in sound velocities are directly influenced by the accuracy of sample thickness measurements. Often, multiple materials (e.g., tantalum and LiF) are bonded together, making glue bond thickness a potentially important parameter. Because glue bond thickness is determined by subtracting individual material thicknesses from the bonded stack thickness, several thickness uncertainties accumulate in the calculation. Furthermore, glue bonds are typically on the order of 1μm thick. For these reasons, small individual errors can compound resulting in error uncertainties greater than the actual thickness itself. Flatness is another important measurement in the characterization of these targets because it couples to dynamic target tilt and two-dimensional wave effects during dynamic experiments.[5]

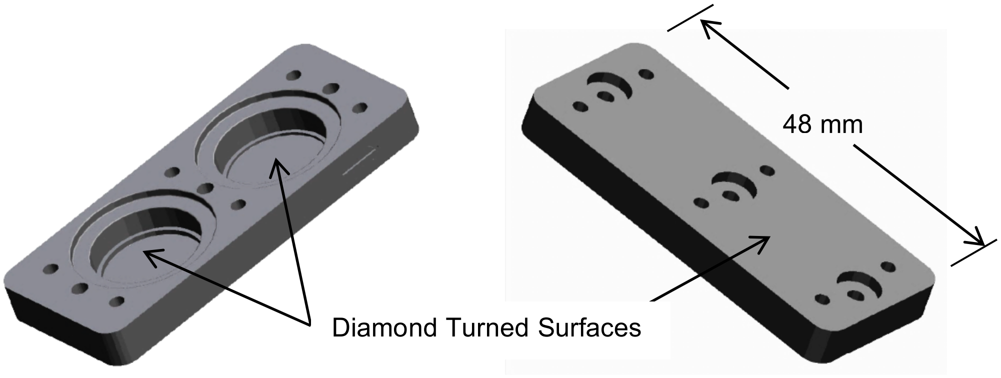
Previously, two methods have been used to measure the thickness of DMP target components for Z (referred to as "our specimens" for the remainder of this paper), but both have had serious drawbacks which have limited the assumed accuracy of thickness data to +/-3μm in experimental analyses. For measuring flatness, the previous instrument adds a burdensome operation to the characterization which is unwelcome in a production environment where it is often required to characterize and assemble a dozen components in one day.

This paper describes a new instrument which was jointly developed by GA and SNL specifically for simultaneously measuring both thickness and flatness of our specimens. The instrument overcomes the shortcomings of both previous methods while yielding at least a four times reduction in thickness uncertainty for specimens of diamond machined copper and aluminum within the thickness range of 0.2mm-3.3mm. It uses dual chromatic, confocal, distance sensors and has numerous features which eliminate the drawbacks of the previous dual confocal designs for the Z target application discussed here.[6-8] Accuracy has yet to be determined on specimens of materials other than copper and aluminum, and of thickness between 3.3mm and the instrument's maximum capability of 6mm, but it is hoped performance will prove to be similar when these tests are completed.

II. PREVIOUS METHODS OF DMP COMPONENT THICKNESS AND FLATNESS MEASUREMENT FOR Z TARGETS

The two tools currently used to characterize thickness and flatness of our specimens have significant drawbacks. One of these tools, which measures thickness only, is a contact-type, digital height gage (Heidenhain CT6001) where one face of a specimen is hand held against an anvil while a probe lightly presses against the opposing face. There are two problems with this method. The first is that compressive forces induced by the anvil and probe inevitably cause small but potentially significant deformation – both temporary and permanent – to the specimen surfaces, leading to measurement errors and, possibly, unwanted experimental effects if damage is excessive. The second problem is that the method is significantly dependent upon operator technique: accurate measurements require manually varying the orientation of the sample relative to the anvil and probe to find the minimum measurement and are consequently overly subjective and of poor reproducibility. Based upon experience, the assumed accuracy of thickness data collected using this tool is +/-3μm in experimental analyses.

The second tool is a Nikon Nexiv VMR-3020, numerically controlled, confocal microscope, equipped with an X-Y positioning stage and autofocus which is used to map flatness of the upper specimen surface. Unfortunately, it is of very little use for measuring thickness of our specimens since the best it can do in that regard is measure specimen height relative to a reference plane – the resulting "thickness" measurements therefore being affected by flatness of the lower specimen surface. Because flatness of our specimens is known from interferometric measurements to be commonly >2µm (Fig. 1), this problem often results in thickness values that are significantly too large.



Top View Bottom View

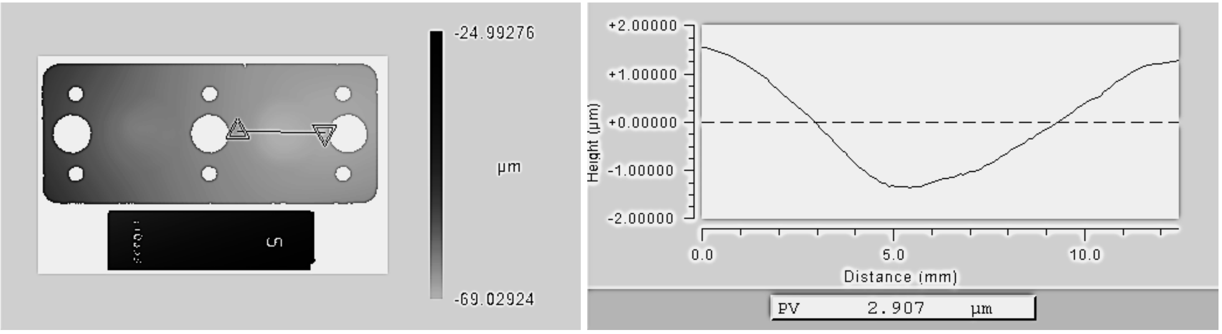


Fig. 1. Interferometric measurement of a DMP target panel used on Z. The lower-right image is a cross section taken between the triangular markers on the image to the lower-left. Note the almost 3µm flatness error.

III. THE ADVANTAGES OF “DUAL CONFOCAL” THICKNESS MEASUREMENT

The “dual confocal” measurement principle, as discussed in this paper, overcomes the thickness measurement problems described above. It employs two confocal distance sensors which are mounted in-line, with the measurement specimen in between, and the sensors simultaneously “looking” at opposing surfaces of the specimen. By subtracting each sensor’s distance measurement from a calibration parameter, the specimen thickness is determined. The calibration parameter is just the sum of the two distance measurements and the known thickness of a standard when it is placed between the sensors. Because the sensors are non-contact and the specimen is mounted on a fixture which orients the measured surfaces perpendicular to the measurement axis, the deformation/damage and subjectivity problems associated with our previous contact measurement method are avoided. Since thickness is measured directly (rather than height above a reference surface) flatness errors of the specimen have no effect on thickness measurements. The sensors have numerous other features making them easy to integrate into instrument designs and nearly ideal for this application: large selection of working distances, compact size, <1µm accuracy capability, perpendicular line of sight enabling measurement close to walls, low sensitivity to surface reflectivity, and small measuring spot diameter.

IV. INSTRUMENT DESIGN CRITERIA

The following are the initial constraints which drove the instrument design.

IV.A. Lateral Travel

Although the largest lateral dimensions of our specimens are approximately 50mm x 50mm (X/Y), which establishes the lower limit of the instrument’s X/Y axes travel, it was decided to enlarge the travel envelope to 126mm x 91mm to fit an array of thickness calibration

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standards which could be automatically accessed during the calibration/verification software routines (see IV.D. below). The larger travel also allows for future increases in specimen size.

IV.B. Flatness Measurement

Another critical system design constraint is the capability to routinely and accurately measure flatness in addition to thickness, significantly improving upon dual confocal systems which are typically designed to accurately measure thickness only. While systems which can measure form or flatness have been built, we are not aware of any dual confocal systems with the ability to do so and certify accuracy to <1µm with a high level of confidence in a production environment.[7] To accomplish this, our approach involves mapping stage travel flatness errors using a flatness standard and then automatically correcting them with software. Measuring flatness with our system, therefore, demands high flatness repeatability of X-Y axis motion since repeatability determines the validity of the stage's flatness map. Because a design requirement of the system is to measure flatness with an accuracy of at least 2µm, of diamond machined copper and aluminum specimens with lateral dimensions of up to 50mm x 50mm, X-Y stage flatness repeatability of 0.2µm (i.e., 1/10th of the required accuracy) is desired within an area of that size, within the +/- 0.1 ºC expected operating temperature range of the instrument during the measurement cycle.

Instead of using a semi-permanent map of stage flatness, the method used in our instrument is to generate a new one immediately prior to taking a flatness measurement on a specimen. Doing so reduces the likelihood of significant differences between mapping temperature and specimen measurement temperature, thereby increasing the reliability of the map, and hopefully eliminating the need for stringent temperature control in the lab. It also enables mapping precisely the unique X-Y locations to be subsequently measured in the specimen, greatly speeding the mapping operation and eliminating map interpolation errors.

Generation of the flatness map of the required area is accomplished by using the most accurate sensor (the lower in our case) to measure distances to a 3” diameter, 1/20λ optical flat which is mounted to the stage. The distance data recorded for all points comprises the flatness map which can be applied to the subsequent measurement data from the specimen. Verification of the map’s accuracy can be accomplished by re-measuring the optical flat after specimen measurement, this time applying the flatness map to the lower sensor data, and verifying <1µm flatness compared to a least-squares fit through the resulting point cloud. This mapping/measurement/verification process requires the ability to quickly install and remove both the optical flat and the specimen to be measured, not only to make immediate mapping practical given the time restrictions imposed by the production environment, but also to minimize temperature variation in the instrument during the process. A requirement for the holding fixtures for the optical flat and specimen, therefore, is that they permit quick changeover.

IV.C. Sensors

Confocal distance sensors are available in a variety of working distances, and their accuracy improves as working distance becomes shorter, so good design practice is to use the shortest working distance possible. All our specimens have at least one side which is nominally flat, with no projecting features, allowing one sensor (the lower sensor in our instrument) to have a very short working distance. As nominal working distance become shorter, however, so does the allowable deviation of the target surface from the nominal working distance. A second design criteria for the holding fixtures for the optical flat and specimen, therefore, is that they must reliably locate the lower specimen surface within the lower sensor's relatively narrow range of working distances.

The upper sensor, on the other hand, must accommodate a large working distance and working distance variability. Although the range of thickness requiring measurement is 0.2mm-6.0mm, overall specimen thickness can be up to 24.5mm due to extraneous features which project from the upper side of the specimen. Maximum working distance for the upper sensor, therefore, must be at least equal to the maximum overall specimen thickness minus the minimum measurement thickness, or 24.3mm. As an additional upper sensor constraint, so that normal operation of the instrument will not require adjustment of the sensor position (thereby greatly simplifying and speeding use of the system in production), allowable working distance variation must be at least equal to the specimen thickness range of 5.8mm.

Sensor linearity is an important criterion in sensor selection, because linearity defines the maximum error of the sensor after calibration. Our requirement for the instrument is <1µm thickness measurement accuracy on diamond machined copper and aluminum samples, but it is not believed <1µm sensor linearity is required to achieve that requirement. Our approach, as described in the following section, is to "calibrate out" the sensor linearity.

IV.D. "Built In" Thickness Standard Array

As discussed in Section IV.A., it was decided to incorporate multiple thickness calibration standards semi-permanently located within the working envelope of the instrument's X-Y stage. The array of standards encompasses the instrument's full thickness measurement range, at very fine thickness intervals so that it not only increases productivity by saving the time that would otherwise be required to install, measure, and remove the required calibration standard before each measurement, and repeat after each measurement as verification, it also improves measurement accuracy in two ways. By reducing the time required for the calibration/measurement/verification process, as well as operator handling of standards, temperature effects are minimized; more importantly, by enabling calibration using a standard which is very near the thickness of the specimen, thickness measurement uncertainty is reduced far below the uncertainty which would be predicted based upon advertised sensor linearity. This is what is meant by the term “calibrating out” the sensor linearity. Because the instrument is intended to measure thickness of 0.2mm-6.0mm thick specimens, a design constraint for the thickness standards is that their lateral size be small enough to enable fitting the entire array into the space available within the working envelope of the instrument.

IV.E. Thermal Effects

Any change to the sensor spacing without a compensating change to the thickness calibration parameter will cause thickness measurement errors, and any change to sensor positions during flatness calibration or flatness measurement results in flatness measurement errors. For these reasons, it is very important to mitigate dimensional changes within the instrument resulting from thermal effects. The flatness and thickness measuring processes have been designed to this end both by minimizing operator handling and time between the mapping/calibration, measurement, and verification steps, as described above. As also described, these process features place constraints upon the hardware design: the instrument’s X-Y travel has been enlarged to accommodate a built-in array of thickness standards, and the holding fixtures for the optical flat and specimen have been designed to allow rapid placement and removal.

Other hardware design features considered desirable for controlling thermal effects include use of materials with higher specific heat (*c*), higher mass (*m*), and lower thermal conductivity (*k*), because these property directions favor temperature stability. Enclosing the entire instrument within a box further reduces sensitivity to ambient air temperature changes.

To minimize dimensional changes due to instrument temperature variations which occur despite the measures mentioned above to control them, the use of materials with low coefficient of thermal expansion (CTE) in critical locations is important. It is believed that the combined effect of these instrument design features to mitigate thermal effects will eliminate the need to closely control ambient temperature and air flow of the lab.

V. INSTRUMENT DESIGN OVERVIEW

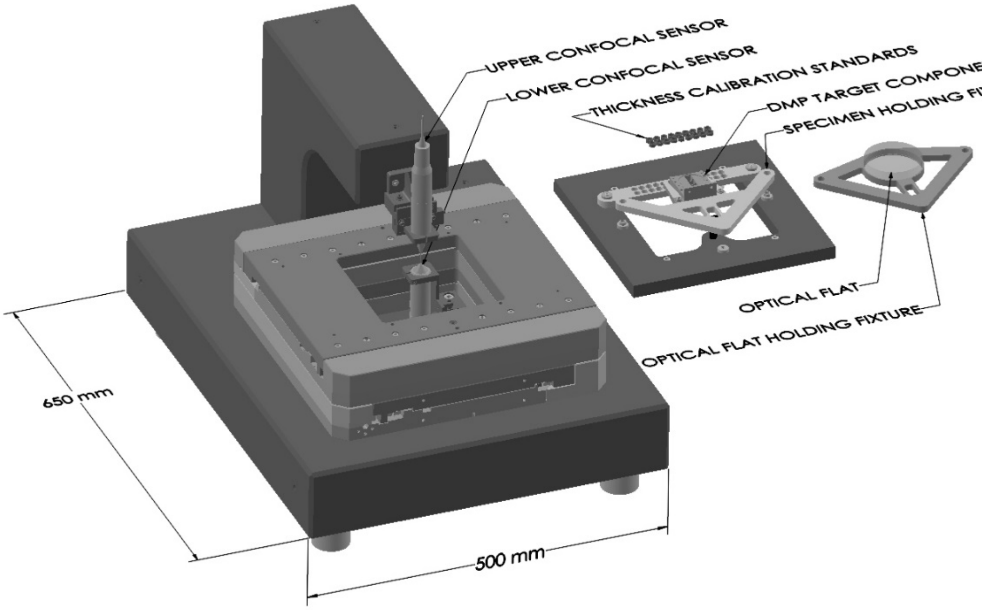


Fig. 2. Enhanced Dual Confocal measurement system with enclosure removed and fixture elements shown to right for clarity.

V.A. X-Y Stage

A specially built version of the Steinmeyer KDT380, precision X-Y stage is used to position the object to be measured laterally between the fixed sensors. By hand fitting the slide components, flatness repeatability of less than 0.05µm within +/-25mm of center (X and Y axes) has been achieved in an environment controlled within 0.1 ºC. The stage has an X-axis travel of +/-65mm and Y-axis travel of +30mm/-65mm; X and Y axes positioning repeatability are +/-1 µm; X and Y axes positioning accuracy are +/-10µm; Maximum speed is 25mm/s. for both axes. The stage more than satisfies the travel and flatness repeatability requirements outlined in Sections IV.A. and IV.B.

V.B. Distance Sensors

Two, Precitec, CHRocodile SE, chromatic, confocal, distance sensors and optical probes are used. The lower optical probe has a working distance range of 4.35mm-4.65mm, distance resolution of 0.010µm, spot diameter of 5µm, and linearity of +/-0.1µm. The upper optical probe has a working distance range of 32.3mm-40.3mm, distance resolution of 0.260µm, spot diameter of 30µm, and linearity of +/-2.6µm. The sensors satisfy the working distance requirements described in Section IV.C., above.

Note: The Precitec CHRocodile SE is a white light, chromatic sensor enabling an order of magnitude improvement in linearity over a tuning fork type of sensor, such as the Keyence, with an equivalent range. For example, the Keyence LT-9011 sensor has an advertised linearity of +/-0.5% of its working distance variation of 0.6mm (i.e., +/-0.3mm), or 3µm. The equivalent Precitech sensor has an advertised linearity of 0.033% of its working distance variation of 0.6mm, or 0.2µm. So, for our lower sensor, the more accurate option is the chromatic type sensor. For our upper sensor, however, the only option is the chromatic type sensor, because a minimum working distance variation of 5.8mm is required to avoid adjusting the sensor position during normal operation (as discussed in Section IV.C.), and such tuning fork sensors are not available.

V.C. Instrument Base

A massive granite structure was chosen due primarily to the thermal and mechanical stability it provides. Dimensional changes in upper sensor mounting column would directly affect sensor positions, as discussed in Section IV.E., and must, therefore, be mitigated. The specific heat of granite is approximately 1.6x that of steel and Invar and 0.9x that of aluminum, hence its ranking as 2nd among the candidate materials for favorability of this property. Granite's density is about equal to that of aluminum and about 0.4x that of steel and Invar, giving steel and Invar a mass advantage if geometry is the same. However, the thermal conductivity of granite is only 0.02x that of aluminum and 0.1x that of steel and 0.2x Invar, giving granite approximately a 3x advantage over the nearest competitor (Invar) in the final analysis of overall temperature stability. Although the CTE of Invar is only 1/4 that of granite, making Invar an attractive alternative, its cost is approximately 2x that of granite and density is 2.5x, which would increase the instrument weight by approximately 200kg, while offering little, if any, actual advantage, since we believe the measures discussed earlier to ensure temperature stability of the instrument will be effective.

V.D. Sensor Mounts

Dimensional changes in the sensor mounts would also directly affect sensor positions and therefore should be constructed of a material with good temperature stability and low CTE such as granite and Invar as just discussed. For the sensor mounts however, Invar is much preferred over granite because of its high machinability, which is required for these pieces since they possess many machined features to permit adjustment of sensor alignment.

V.E. Holding Fixtures

Invar was also chosen for the holding fixtures for the optical flat and specimen. Although dimensional changes to these pieces would not affect thickness measurement, they would affect both flatness calibration and flatness measurement, making good temperature stability and low CTE also advantageous for these items. The holding fixtures are positioned and oriented in the X-Y plane by a pin and diamond pin arrangement, and are positioned in the Z direction by resting on three pads. Location tolerances of +/- 50µm are sufficient for the optical flat and specimen, so kinematic mounting is not required. Location stability during calibration and measurement is critical, however, so a custom, quarter-turn tensioner is employed to lightly spring load the fixtures against the locating pads. The measuring specimens rest on narrow shelves which are machined into parallel Invar “fingers,” one of which slides on a precision dovetail to permit adjustment for specimen width. Round or odd shaped specimens are accommodated by first mounting them in rectangular adapter blocks. Generally, free state measurements are preferred, so a few small tacks of hot glue are used to prevent specimens from shifting during measurement rather than clamping. Two fixtures are available to enable mounting the next specimen on a workbench while performing measurements on another, increasing productivity and minimizing opportunity for instrument temperature changes.

V.F. Software and Operation

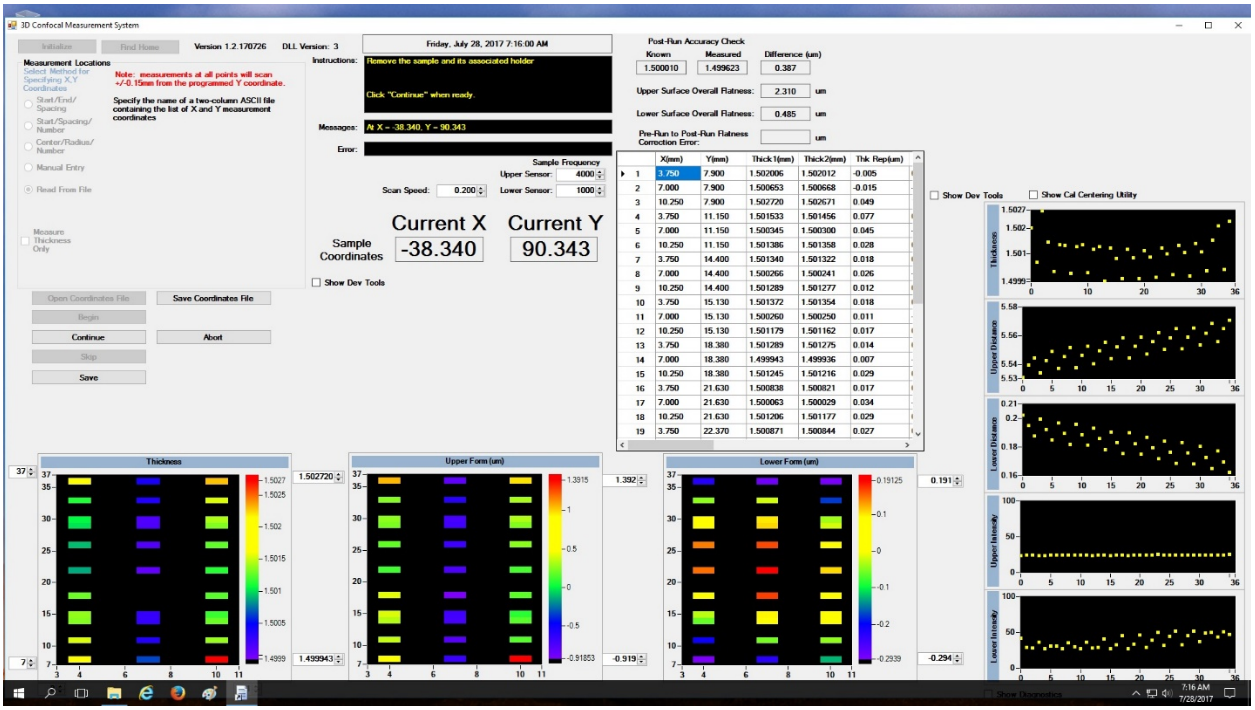
All instrument motion as well as data acquisition and analysis are controlled through a custom Windows application (Fig. 3). The following are the operational steps for specimen measurement:

1) **Specify the measurement locations.** To facilitate this, the user interface presents built in strategies for simplified definition of uniformly distributed locations within user-defined circular and rectangular areas, since these are very common specimen shapes. Alternatively, specific X-Y coordinates may be input or read from a file to accommodate special tasks and geometries.
2) **Install and measure the optical flat (optional).** The operator is prompted to install the optical flat which is semi-permanently mounted in its own fixture. If only thickness is to be measured this step is omitted by first checking a “thickness only” box in the user interface. Upon operator command, the optical flat is measured at the X-Y coordinates just defined, automatically creating the flatness compensation map (see Section IV.B.).
3) **Install and measure the specimen (with automatic thickness calibration and verification).** The operator is prompted to remove the optical flat (if present) and replace it with the specimen which has been previously installed into its holding fixture “off line.” The operator is also prompted to input the nominal specimen thickness. Upon operator command, the instrument automatically positions the calibration standard of nearest thickness between the sensors and performs the thickness calibration, then measures the specimen at the defined locations, then, finally, automatically measures the standard of next-nearest thickness to provide

verification. An option is also presented to remeasure the specimen so repeatability of thickness data can be assessed.

4) **Confirm flatness calibration (optional).** The software prompts for remeasurement of the optical flat as a means of confirming accuracy of the flatness compensation map if desired.

5) **Output and store data.** Upon completion of measurements, flatness, and thickness results are automatically output in numerical and graphical form within the software's user interface. Numerical data is stored in ASCII format suitable for export into Excel or other 3rd party data analysis/display applications.



Version 1.2.170726 DLL Version: 3

Friday, July 28, 2017 7:16:00 AM

Note: measurements at all points will scan +/-0.15mm from the programmed Y coordinate.

Specify the name of a two-column ASCII file containing the list of X and Y measurement coordinates

Instructions: Remove the sample and its associated holder

Click "Continue" when ready.

Messages: At X = -38.340, Y = 90.343

Error:

Sample Frequency
Upper Sensor: 4000
Lower Sensor: 1000
Scan Speed: 0.200

Sample Coordinates
Current X: -38.340
Current Y: 90.343

Post-Run Accuracy Check

Known	Measured	Difference (um)
1.500010	1.499623	0.387

Upper Surface Overall Flatness: 2.310 um
Lower Surface Overall Flatness: 0.485 um
Pre-Run to Post-Run Flatness Correction Error: um

	X(mm)	Y(mm)	Thick1(mm)	Thick2(mm)	Thk Rep(um)
1	3.750	7.900	1.502006	1.502012	-0.005
2	7.000	7.900	1.500653	1.500668	-0.015
3	10.250	7.900	1.502720	1.502671	0.049
4	3.750	11.150	1.501533	1.501456	0.077
5	7.000	11.150	1.500345	1.500300	0.045
6	10.250	11.150	1.501386	1.501358	0.028
7	3.750	14.400	1.501340	1.501322	0.018
8	7.000	14.400	1.500266	1.500241	0.026
9	10.250	14.400	1.501289	1.501277	0.012
10	3.750	15.130	1.501372	1.501354	0.018
11	7.000	15.130	1.500260	1.500250	0.011
12	10.250	15.130	1.501179	1.501162	0.017
13	3.750	18.380	1.501289	1.501275	0.014
14	7.000	18.380	1.499943	1.499936	0.007
15	10.250	18.380	1.501245	1.501216	0.029
16	3.750	21.630	1.500838	1.500821	0.017
17	7.000	21.630	1.500063	1.500029	0.034
18	10.250	21.630	1.501206	1.501177	0.029
19	3.750	22.370	1.500871	1.500844	0.027

Fig. 3. Custom Windows application user interface.

V.G. Thickness Calibration Standards

Critical to the accuracy of the instrument are the thickness calibration standards as discussed in Section IV.D. The lower surface of the standards is flat while the upper surface has a 1mm diameter flat center pocket surrounded by 6 concentric steps, each 50µm tall and 500µm wide, forming 7 different thickness zones and a thickness range of 350µm per standard (Fig. 4). The upper and lower surfaces are produced by diamond turning to ~10nm Ra to simulate the surface roughness of our specimens as well as to give high thickness uniformity. Each standard has an alignment notch which, together with the standard's center, establishes a radial axis along which the steps are calibrated as described in the following section. These calibration axes of the standards are precisely oriented in the instrument which enables pre-programming the calibrated locations of all the standards in the thickness calibration array. When thickness calibration and verification of the instrument are performed during normal operation, therefore, entering the nominal thickness value for the specimen to be measured is sufficient for the instrument to automatically locate the standards nearest the specimen thickness. The upper and lower standard surfaces are machined parallel within 1µm so that large errors in the orientation of the standards within the holder would be required for the thickness at the location measured during the calibration or verification cycle to vary significantly from the standard's calibrated value. The standard array currently consists of 9 aluminum and 9 copper standards, covering the thickness range of 0.2mm-3.3mm for each material, since this is the thickness range of our specimens of aluminum and copper, but the standard holder can accommodate up to 26 standards (Fig. 5). Aluminum and copper were chosen for the thickness standard materials because nearly all the DMP targets on Z utilize one or both materials in critical locations, in addition to other materials that may be used to suit the experiment, and using the same material for the standards as is used for the specimens ensures the instrument can, at a minimum, provide accurate measurements on our most common specimens.

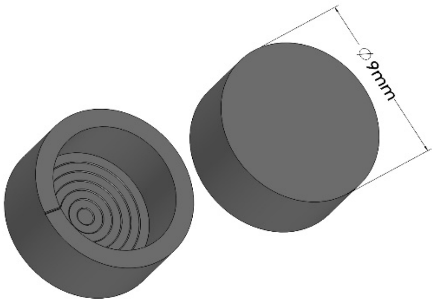


Fig. 4. Top and bottom of thickness calibration standard showing seven thickness steps.

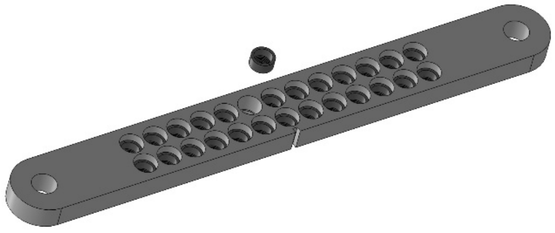


Fig. 5. Thickness calibration standards (26) and holder.

VI. Thickness Standard Calibration

A Zygo NewView 7300 white light interferometer and a special technique were used to calibrate the thickness standards. The center hole of a 1" square x 2mm thick, Grade 00 gage block was bored to a slip fit for the OD of the standards, permitting a standard to be glued inside with its flat face nominally coincident with one face of the gage block (Fig. 6). Using a 1x objective with 0.5x zoom lens, a single interferometric scan was taken which included one side of the glued assembly with the 9mm diameter standard centered within the scan, thereby giving a height map of the entire 14.1mm x 10.6mm scan area with X-Y resolution of 44µm. The Z coordinates of the resulting data were then shifted and rotated to transform the Z origin to 4 areas on the gage block surface symmetrically surrounding the thickness standard, the resulting dataset thus containing the Z coordinate of each pixel in the scan relative to a best fit, Z origin plane passing through the 4 gage block areas. The assembly was then flipped over and the other side was similarly scanned and transformed, but this time, the data was also mirrored about the flipping axis to yield a dataset which, when added to the first, gives the thickness of the standard minus the thickness of the gage block at each pixel location (Fig. 7). The final step to get the standard thickness at each pixel location is simply to add the gage block thickness to each data point. The Zygo MetroPro software has all the data manipulation functionality just described built in, so no processing outside of MetroPro is required.

Fig. 6. Copper thickness standard glued into 2mm gage block with alignment notch visible.

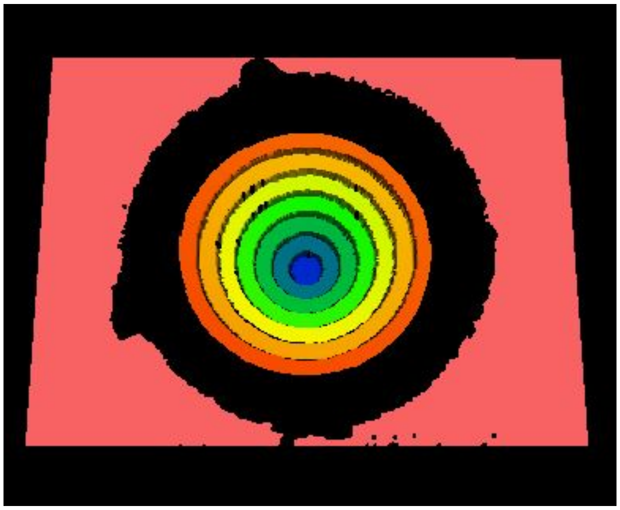


Fig. 7. Sum of upper and lower Zygo scans of assembly shown in Fig. 6.

Expanded uncertainty of the thickness determined using the interferometric method just described is determined as follows:

1. Standard uncertainty (σ) of Zygo extended scan used for stepped side of thickness standard (30 measurement sample size): +/- 0.080µm
2. Standard uncertainty (σ) of Zygo standard scan used for flat side of thickness standard (30 measurement sample size): +/- 0.001µm

3. Standard Uncertainty (σ) of 2.542590mm gage block used for calibration of Zygo extended scanning: +/- 0.030μm

4. Standard Uncertainty (σ) of 2mm gage block in Fig. 6 used for measurement comparison: +/- 0.030μm

5. Standard Uncertainty (σ) of best fit planes to upper and lower gage block surfaces: +/- 0.200μm (estimated)

<u>Combined Uncertainty</u>:

Combined Standard Uncertainty (σ) = $[(0.08)^2 + (0.001)^2 + (0.03)^2 + (0.03)^2 + (0.20)^2]^{1/2}$ = +/- 0.22μm

Combined Expanded Uncertainty (2σ = 95% confidence) = +/- 0.44μm

As a test of the method's accuracy, a gage block was substituted for the thickness standard in the center of the gage block in Fig. 6. The calibrated thickness was certified by the manufacturer (Starrett) as 2.000150mm +/-0.000090mm (σ). Using the interferometer method described above, the measured thickness was 2.000280mm, well within the +/-0.44μm expanded uncertainty calculated above for the method, giving confidence that the method is valid.

VII. Results

The instrument was completed very shortly before the writing and of this paper so extensive testing and evaluation has not yet been performed, but preliminary indications are positive. We have measured approximately two dozen of our specimens and have found remeasurement of the optical flat after specimen measurements (Section V.F., Step 4) has consistently yielded flatness values of less than 0.1µm, indicating validity of the flatness compensation map applied to the specimen measurements and the absence of thermal effects which significantly degrade measurement accuracy. Further, measuring the standard of next-nearest thickness after specimen measurements (Section V.F., Step 3) has consistently produced results which agree to better than 1µm of the standard's calibrated thickness, as would be expected given the small uncertainties in the thickness standard calibrations. Remeasurement of the specimens has yielded thickness variations consistently below 0.1µm, also providing confidence.

VIII. Future Work

We plan to conduct testing to determine whether thickness standards of both copper and aluminum are really required. If we find calibration of the instrument using a thickness standard of copper produces accurate measurements on a thickness standard of aluminum, and vice versa, we would know there is no need for thickness standards of both materials. We also plan to make thickness standards from Cupronickel and compare them to those of copper and aluminum. Cupronickel is diamond turnable and extremely corrosion resistant, so it makes a nearly ideal material for our application. If cupronickel turns out to measure the same as copper and aluminum in our instrument, it will be substituted for them, thereby extending the useful life of the standards indefinitely and allowing all the thickness standards required to cover the instrument's full thickness measurement capacity of 0.2mm-6mm to be contained within just one holder. At present, we have not quantified the contribution from sensor linearity to the accuracy of the instrument, instead, assume that it is negligible due to the very fine thickness intervals of the thickness standards. However, it may be possible to estimate the sensor linearity contribution in the future by measuring gage blocks or other certified standards of thickness between our thickness standard intervals. Finally, certification of system accuracy on specimens of other than copper and aluminum should be undertaken to extend the instruments usefulness to other DMP target components. Polished steel should be included among these materials since it would allow the use of gage blocks for accuracy confirmation.

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