Terahertz reflection interferometry for automobile paint layer thickness measurement

Aunik Rahman[1], Kenneth Tator[2], Anis Rahman[1],*
[1]Applied Research & Photonics, Inc., 470 Friendship Road, Suite 10, Harrisburg, PA 17111
[2]KTA-Tator, Inc., 115 Technology Drive, Pittsburgh, PA 15275
*email: a.rahman@arphotonics.net

ABSTRACT

Non-destructive terahertz reflection interferometry offers many advantages for sub-surface inspection such as interrogation of hidden defects and measurement of layers' thicknesses. Here, we describe a terahertz reflection interferometry (TRI) technique for non-contact measurement of paint panels where the paint is comprised of different layers of primer, basecoat, topcoat and clearcoat. Terahertz interferograms were generated by reflection from different layers of paints on a metallic substrate. These interferograms' peak spacing arising from the delay-time response of respective layers, allow one to model the thicknesses of the constituent layers. Interferograms generated at different incident angles show that the interferograms are more pronounced at certain angles than others. This "optimum" angle is also a function of different paint and substrate combinations. An automated angular scanning algorithm helps visualizing the evolution of the interferograms as a function of incident angle and also enables the identification of optimum reflection angle for a given paint-substrate combination. Additionally, scanning at different points on a substrate reveals that there are observable variations from one point to another of the same sample over its entire surface area. This ability may be used as a quality control tool for in-situ inspection in a production line.

Keywords: Terahertz reflective interferometry, Paint and coating layers, Non-destructive thickness determination, Sub-surface layer thickness measurement, Interferometry thickness modeling, Automated scanning and quality control.

1. INTRODUCTION

A terahertz reflective interferometer (TRI) has been developed and tested that has the potential for revolutionizing the analysis capabilities which could transform established procedures and protocols in a number of important applications, especially in paint/coatings' thickness measurement in a non-destructive fashion. The TRI was designed based on a dendrimer dipole excitation (DDE) based terahertz source [1–3]. The functionality of the TRI is schematically shown in Fig. 1 (a). A superposed terahertz beam is reflected off of the sample (panel) with multiple layers of coatings. Since terahertz radiation (T-ray) can penetrate the paint materials, the reflections of all the layers are collected into the detection system. As outlined in Fig. 1, the interferometer works based on the diffused reflection of the T-ray from the paint layers. The TRI houses two separate arms; a scanning arm and a probing arm. Probing arm beam overlapped with the scanning arm beam produces interference patterns due to consecutive reflections off of the layers of paint on a panel. This interference patterns are captured as a function of optical delay-time (mm) as they evolve for each layer. The major peaks of these interferograms are the basis for modeling the layer thicknesses as a function of the interference peaks' delay position.

2. EXPERIMENTAL

2.1. Samples

The following samples were supplied (see Fig. 2) by KTA-Tator, Inc., Pittsburgh, PA. Sample KTA-1A is a 4″×8″ blast cleaned hot-rolled steel test panel and KTA-1B is a 4″×12″ cold-rolled steel Q-panel; each coated with the following paint/coating: Layer 1: Amercoat 68 HS-zinc rich epoxy primer; Layer 2: Amercoat 435 Beige-micaceous iron oxide, Recoatable polyamide epoxy; and Layer 3: Amercoat 450H- acrylic aliphatic polyurethane topcoat. Sample KTA-2A

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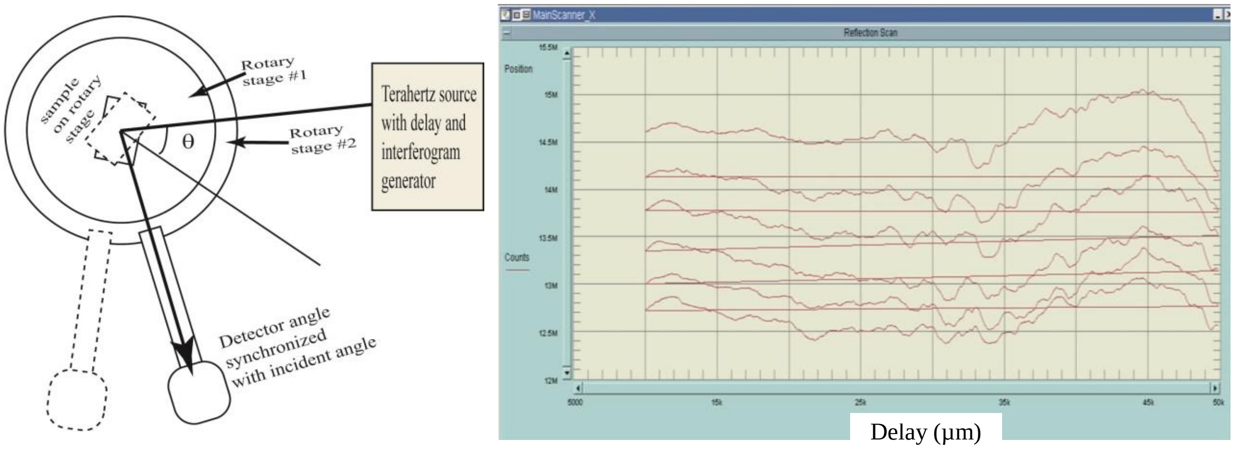

Fig. 1. Left: A schematic diagram of the terahertz reflective interferometer (TRI) with synchronized angular scanning capability. The terahertz source module houses an optical delay line. The detector and the sample positions are synchronized for receiving the beam reflected by the sample. Right: Screenshot of the TRI front-end. Traces at different incident angle are shown over a broad scan length.

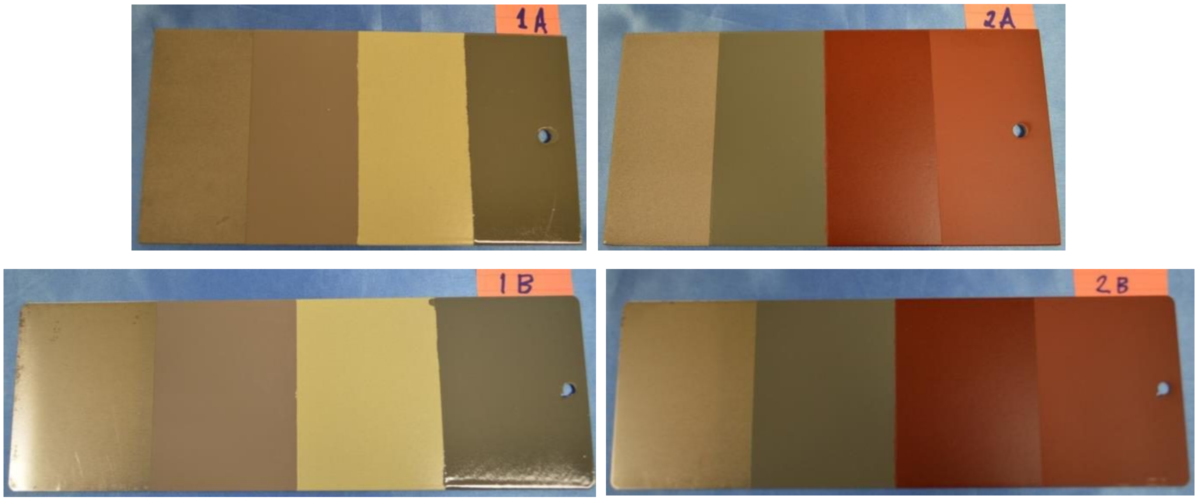

Fig. 2. Photograph of samples 1A, 2A, 1B and 2B as described above.

and KTA-2B are similar set of panels as before except they are coated using a Cosco Kansai system as follows: Layer 1: SC Zinc Primer-2K epoxy resin and hardener, added zinc dust, prime coat; Layer 2: Epomarine SC Primer-epoxy resin and polyamide harder, intermediate coat; and Layer 3: Acric SC Brown-modified acrylic resin, topcoat. Thus, all samples have 4 segments: (1) a bare substrate (left most), (2) Layer 1, (3) Layer 1 + 2, and (4) Layer 1 + 2 + 3. While there was no coat applied on the layer 1 (bare segment of the panels), however, we found that there is a measurable reading on the bare segment of all four panels. This was also verified by the DualScope reading; and both procedures produced similar results.

The above mentioned samples were measured on the TRI (Applied Research & Photonics, Harrisburg, PA). Fig. 1 (b) shows the dependence of scanning traces on the incident angle. It is seen that the reflected intensity is higher at some incident angle than others. An optimum angle of 45° was determined for the samples of the present study. Therefore, all subsequent measurements were carried out at a fixed incident angle of 45°. Samples were mounted one at a time on the TRI and the delay scan was conducted. The reflected intensity as a function of delay was collected by the TRI front-end software. Interferograms thus acquired were stored in respective data files for each sample. The interferograms were then analyzed as described below for computing the layer thicknesses.

3. RESULTS AND DISCUSSION

Fig. 3 shows the measured interferograms for all four samples. The left column of Fig. 3 shows a broad scan for all four samples (i.e., 1A, 2A, 1B & 2B) over a delay length of 50 mm and the right panels identifies the specific interference peaks utilized for thickness modeling. As can be seen from the interferograms, there are strong correlation of the interference peaks due to reflection from different layers as the probing beam scans the sample. The challenge, however, is in utilizing the appropriate consecutive peaks for the layer thickness calculation. In the present report, a Fischer DualScope thickness gauge was used for an independent measurement of the paint thicknesses. It was found that, there are significant differences in layer thickness over different areas of a sample. However, several measurements were taken over each layer and the average is shown in Table 2. It is observed that the peak positions and measured layer thicknesses by DualScope, qualitatively exhibit the same trend. The task, then, is to find an empirical model for a given paint/substrate combination to deduce the layer thicknesses from the interferogram's peak position values. Certainly, other factors relating to the optical properties of the coating played a role in forming the interferograms; as such, a model may also be dependent on those physical parameters. Furthermore, it is possible that in some cases the index of refraction of a subsequent layer will be lower or higher than the one above. In such cases, the trough or negative peak should be used as opposed to the crest or positive peak. Therefore, the effect of refractive indices on the interference peaks need to be investigated.

3.1. Paint Layer Thickness Modelling

Table 1 shows the data for four different samples obtained by the Fischer DualScope and also from the interference peaks analysis. A plot of the thickness data obtained by both methods is depicted in Fig. 4. The layer thicknesses were modelled for each sample by comparing the trend for both the DualScope readings and the cumulative interferogram peak data. Once the trends for both were found, an empirical equation was used as follows. Assuming the trend of the DualScope (DS) data is given by $Y_{DS} = m_{DS}X + c_{DS}$ and the cumulative interference peak (IP) position trend is given by $Y_{IP} = m_{IP}X + c_{IP}$, then the ratio of Y_{IP} to Y_{DS}, yields the required factor (a vector) for calculating the thickness of each layer from the interference peak position data. While a linear relationship was applicable for the present set of samples, it is quite possible that there are other specimens where the cumulative peak values may not be of linear nature. In such cases, Y_{IP} and Y_{DS} will be fitted by an appropriate equation (linear or non-linear). Finally, this model calculation for each known samples will form a library from which an unknown sample's layer thickness will be readily determined from measured interferograms' peak positions. Thus a robust library is envisioned where the empirical relationships of different kind of paint/substrate combinations will be stored. These empirical formulas will for the signature of each paint class for a given substrate that will be used for non-destructive determination of the respective layers' thicknesses.

3.2. Future work

The Terahertz Reflective Interferometry technique discussed herein is a powerful tool for resolving multiple paint/coating layers in a non-contact, non-destructive fashion. However, the following improvements are envisioned. Software: Many of the data acquisition and analysis steps may further be automated by suitable software development. The main tasks are: picking the right peak positions via an automated algorithm and then to build a reference library for investigation of unknown samples. Library: It is important that each coating material be modelled for different thicknesses. The shifts in peak positions due to increasing thickness will yield information to incorporate into the model. Once such a library is attained, it will then be utilized for a better understanding of interference peak-thickness relationships, leading to refinement of model calculation. Thus, various relevant basecoats, clear-coats, primers, paints and other coatings should be analyzed to determine the effect of increasing thickness on interference peak shifts. Sample handler: Due to the inherent sensitivity of the TRI, rigid and precise mounting and positioning of the sample are

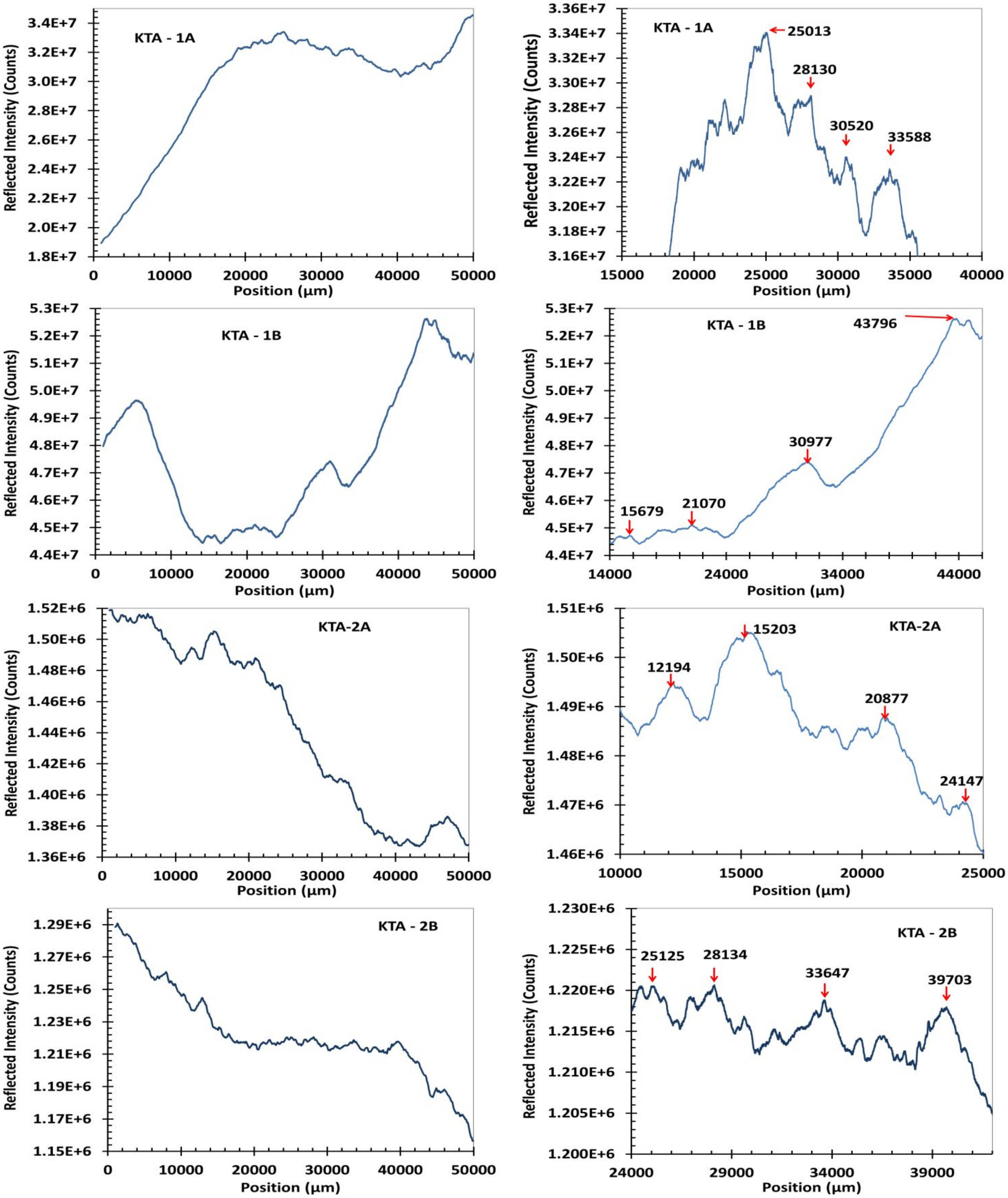

Fig. 3. Interferogram of samples KTA-1A – KTA-2B. Left panel depicts a broad scan over a delay length of up to 50 mm. Right panel depicts the close up of the peak positions utilized for thickness computation (indicated by arrows). See Table 1.

Table 1: Layers' thicknesses determined from the interference peak data (model) and compared to DualScope data.

Sample	Layer#	DualScope Cumulative (µm)	Interference Peak Positions (µm)	Peak Cumulative (µm)	Thickness Model (µm)
1A	1	**7.37**	25013	25013	**4.84**
	2	**86.11**	28130	53143	**93.69**
	3	**195.33**	30520	83663	**187.75**
	4	**284.48**	33588	117251	**287.01**
1B	1	**6.10**	15679	15679	**5.19**
	2	**59.69**	21070	36749	**62.39**
	3	**120.14**	30977	67726	**117.44**
	4	**169.42**	43796	111522	**170.32**
2A	1	**2.54**	12194	12194	**2.96**
	2	**91.44**	15203	27397	**90.18**
	3	**170.18**	20877	48274	**171.44**
	4	**247.14**	24147	72421	**246.72**
2B*	1	**2.54**	25125	25125	**2.54**
	2	**79.25**	28134	53259	**79.25**
	3	**159.00**	33647	86906	**159.00**
	4	**154.94**	39703	*	*

*For this sample, the aggregate of 4 layers' thickness was less than that of the aggregate of first 3 layers. Therefore, model calculation has been applied only to the first 3 layers.

important. Therefore, a pneumatic table and custom sample handling mounts should be developed. Given the sensitivity of the instrument, it can detect the minute differences on a sample surface only few microns apart. Thus, an automated positioning system can be used to precisely position the sample and recall its positions. An automated XYZ positioner could be added for probing various points or a given segment of a sample without requiring manual mounting and demounting. Such an automated setup will also aid in 3D imaging which could be important for some samples. Fiber-optic probe: The instrument may also be fitted with a fiber-optic probe that will allow inspection of objects that may not be moved.

Summary

A terahertz reflective interferometer has been developed for paint/coating analysis. The system has been demonstrated by measuring multi-layered paint samples received from KTA-Tator Inc. While the results are encouraging, however, libraries need to be established before tackling samples of unknown nature. Terahertz time-domain interferograms generated by reflection from different layers of paints on a metallic substrate were used to calculate individual layer's thickness. Interferograms generated at different incident angles show that the interferograms are more pronounced at certain angles than others. This "optimum" angle is also a function of different paint and substrate combinations. The thicknesses generated by the interferogram's peak modeling agree well with the independent measurement by a Fischer DualScope. Therefore, this technique may be used for both laboratory characterization as well as a quality control tool for in-situ inspection in a production line.

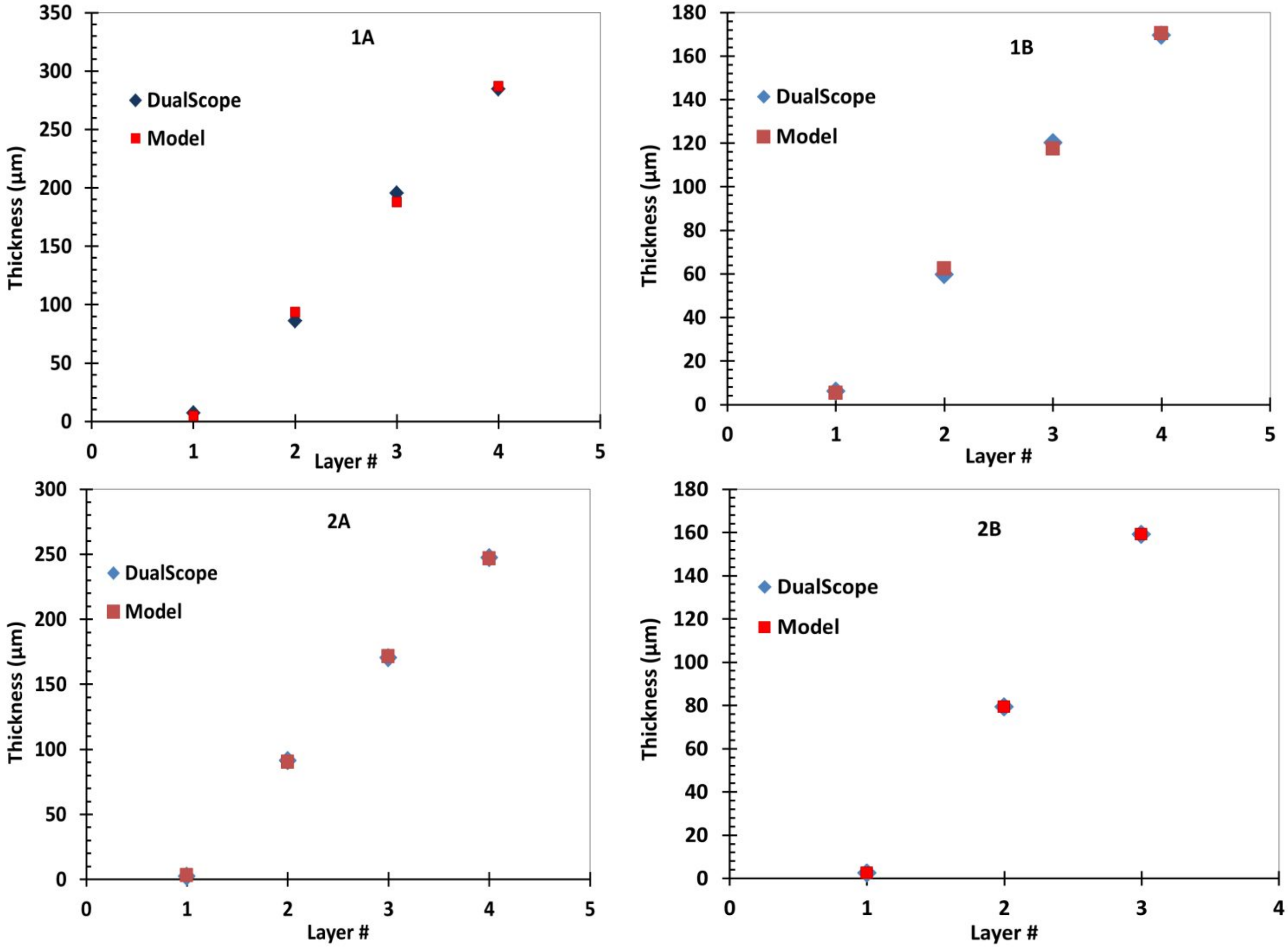

Fig. 4. Layer thicknesses calculated for all four samples and compared to DualScope data. A reasonable match is observed.

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