Flash pulse phase thermography for a paint thickness determination

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Abstract. The contribution describes a fast contactless measurement of a paint thickness non-uniformity using flash pulse thermography. Specimens sprayed by a paint were thermally excited by a flash lamp and temperature responses were recorded by an infrared camera. The recorded sequences were post-processed with Fast Fourier Transform to obtain phase angles. Differences in the resulting images showed phase differences which corresponded to a paint thickness non-uniformity. Furthermore, the phases were correlated with the thickness by means of calibration curve so that the paint thickness could be determined with flash pulse phase thermography measurement. The method showed a promising potential in the contactless evaluation of the paint thickness. Average error of the thickness determination was less than 10 % for samples with paint thickness from 41 to 74 μm on AISI 304 substrate. Advantages, disadvantages and limitations of described method were discussed.

1 Introduction

Paint thickness is one of the key parameter when dealing with paints. The thickness can influence both decorative and functional properties. Among decorative flaws belong blistering, blooming, sagging and many more. Paints used in industry usually have some function for example a protection against corrosion, heat, acids. The problem isn't just insufficient amount of a paint which causes that required properties (e.g. anticorrosion) are not met but also a surplus of paint which leads to increase of weight of painted part, economic losses (less paint cost less) and in some cases decrease of adhesion.

The paint thickness is therefore often tested in industry. Nondestructive thickness measurement can be performed by many different techniques. One of the most used are [1]: measurement with magnetic gauges, ultrasound testing, measuring with devices based on magnetic induction or based on eddy current. Some more advanced and more expensive techniques can be also used as beta-backscatter measuring method [2] and X-Ray fluorescence [2]. They measure thickness but also provide some additional information. The reason for existence of that many techniques is that just limited number of materials can be measured with each of them. For example, with magnetic induction method the thickness can be determined just for non-magnetizable paint on magnetizable substrate. For eddy current (amplitude sensitive) the substrate must be from electrically conductive material. All mentioned techniques take thickness readings from a point. When many readings need to be acquired, the measurement process can be time demanding. Because of that a technique which would provide readings from the whole surface could speed up the thickness measurement. In this contribution we introduce technique for a planar thickness determination based on flash pulse phase thermography [3].

2 Thickness determination using flash pulse phase thermography

Flash pulse thermography (FPT) is an inspection method which belongs to infrared nondestructive testing [3]. The technique is based on excitation of tested subject by a flash lamp with one short pulse (few ms). The temperature response to this pulse is recorded by an infrared camera. This response can show changes in heat transfer caused by defects. Those defects can be for example cracks, delaminations but also uneven thickness of a coating (paint). The result of FPT measurement is a sequence of thermograms (images with temperature distribution). This sequence is then post-processed with an algorithm to enhance defect detectability. To the most popular post-processing techniques belongs pulse phase thermography [4]. This technique is based on post-processing with Fast Fourier Transform. The result is a new sequence where images are in phases or in amplitudes and time is transformed to frequency. In general phase images are more used, especially due to less sensitivity to uneven heating. The thickness of coating can be retrieved via calibration curve phase-thickness as was demonstrated in [5] or [6] for thermal barrier coatings. The principle is that the phases are dependent on thickness of coating, when no additional damages or thermal properties changes are present. There were also some other attempts to determine thickness with FPT as is shown in table 1. The thickness determination was mostly tested on thermal barrier coatings (TBC) with different error in thickness determination (from 5.35 to 59 %). Detection of paint thickness inhomogeneity was published in [7], but a quantification of thickness measurement results was not performed. A goal for this contribution was to determine if it is possible to use PPT for estimating thickness of paint even for thicknesses which are around several tens of μm.

Table 1. Summary of FPT for thickness determination.

Method	Camera wavelength	Camera framerate (fps)	Coating	Thickness (mm)	Error in thickness determination (%)	Source
FPT	Not specified	Not specified	TBC (ZrO2)	0.25-1.5	15.69	[8]
FPT	Long (7.5-13 um)	50	TBC (ZrO2)	0.1-0.6	5.35	[6]
FPT simulation	Not specified	Not specified	TBC (ZrO2)	0.1-0.6	2.35	[5]
FPT	Long (8-9 um)	60	TBC (ZrO2)	0.15-0.3	59	[9]
FPT	Middle (2.5-5 um)	100	TBC (SiC)	0.04-0.12	8.2*	[10]
FPT	Long (8-14 um)	60	Paint	0.01-0.25	Not specified	[7]
FPT	Long	1000	Polymer coating	0.1-2	4.1	[11]
FPT	Long	70	TBC (ZrO2)	0.05-0.13	10	[12]

* calculated by us from data

3 Description of experiment

Two specimens from AISI 304 steel with dimensions 100 x 50 x 2 mm were painted with a black paint (LabIR HERP-LT-MWIR-BK-11). The paint was unevenly sprayed on the surface of specimens. Experimental measurement was performed on both samples. IR camera FLIR SC 7650 was used for thermographic measurement. The framerate was 250 Hz and 1000 frames were recorded. Specimens were excited by 6000 J flash lamp. Center of the tested specimen was in the center of the flash lamp during measurements. The flash lamp was 38 cm from the tested specimen and was perpendicular to the

specimen. Special measures had to be taken considering synchronization of the IR camera and the flash lamp. This is crucial for the thickness estimation. Without synchronization it is possible to detect inhomogeneity in thickness but the phases differ even for repeated measurement. This is caused by capturing frames in different times after excitation. The used device allowed that the IR camera and the lamp were synchronized with precision of +/- 2 μs, which was sufficient for the thickness estimation.
The result of PPT is a sequence. Phase values differ in each frame. Therefore, it is necessary to choose a frame which will be further analyzed. We chose frame which corresponded to frequency 2.25 Hz because it showed highest differences in phases in the area of specimens.

During measurement we encountered a problem which can significantly influence results. With a high framerate (in this case 250 Hz) the camera sometimes skipped some frames. Several measurements were performed for one specimen and all of them contained frames drops. This is a problem for calculating phases because data for FFT have to be evenly spaced. If they are not, phases can differ when important frames (especially those after excitation) are missing. Therefore, the raw data was fitted with an artificial function. The coefficients of this function were retrieved. Fitted temperature response was calculated for evenly spaced time with time difference of 1/250 (frequency of the camera). The equation of fitting function is shown in equation 1.

$$f(t) = K_0 + K_1 \cdot \log t + K_2 \cdot (\log t)^2 + K_n \cdot (\log t)^n \quad (1)$$

, where K_0-K_n are constants and t is time.
With this fitting noise were also suppressed. FFT was then applied to fitted data and the frame which corresponded to frequency 2.25 Hz was used for further analysis. To show difference between raw and fitted data we presented both results.

Specimen 1 was used for creating a calibration curve. Thickness of several points of specimen 1 had been measured with thickness meter (combination of eddy current and magnetic induction principle). The aim was to find points which cover the whole thickness range of sprayed paint. Phase values of those points were then obtained from the phase image of specimen 1. Therefore, it was possible to assign thickness values to phase values. Curve fitting App from Matlab were used to get an equation of calibration curve (equation 2). This equation allows estimation of paint thickness based on the phase.

$$z_c = C_1 \cdot \Phi^3 + C_2 \cdot \Phi^2 + C_3 \cdot \Phi + C_4 \quad (2)$$

, where z_c is thickness, C_1-C_4 are constants and Φ is the phase angle.

4 Results

Figure 1 shows position of points used for creation of calibration curves. These points covered thickness range from 41 to 74 μm. Phase values are in table 2.

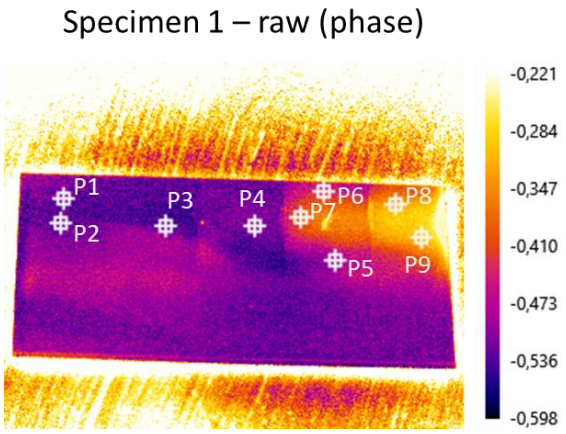

Figure 1. Position of points for calibration curve (phase image).

Table 2. Calibration points.

Point	P1	P2	P3	P4	P5	P6	P7	P8	P9
Thickness (µm)	41	47	52	54	56	60	66	73	74
Phase Raw (rad)	-0.584	-0.519	-0.516	-0.506	-0.502	-0.431	-0.409	-0.332	-0.266
Phase Fitted (rad)	-0.521	-0.493	-0.486	-0.479	-0.459	-0.431	-0.359	-0.272	-0.211

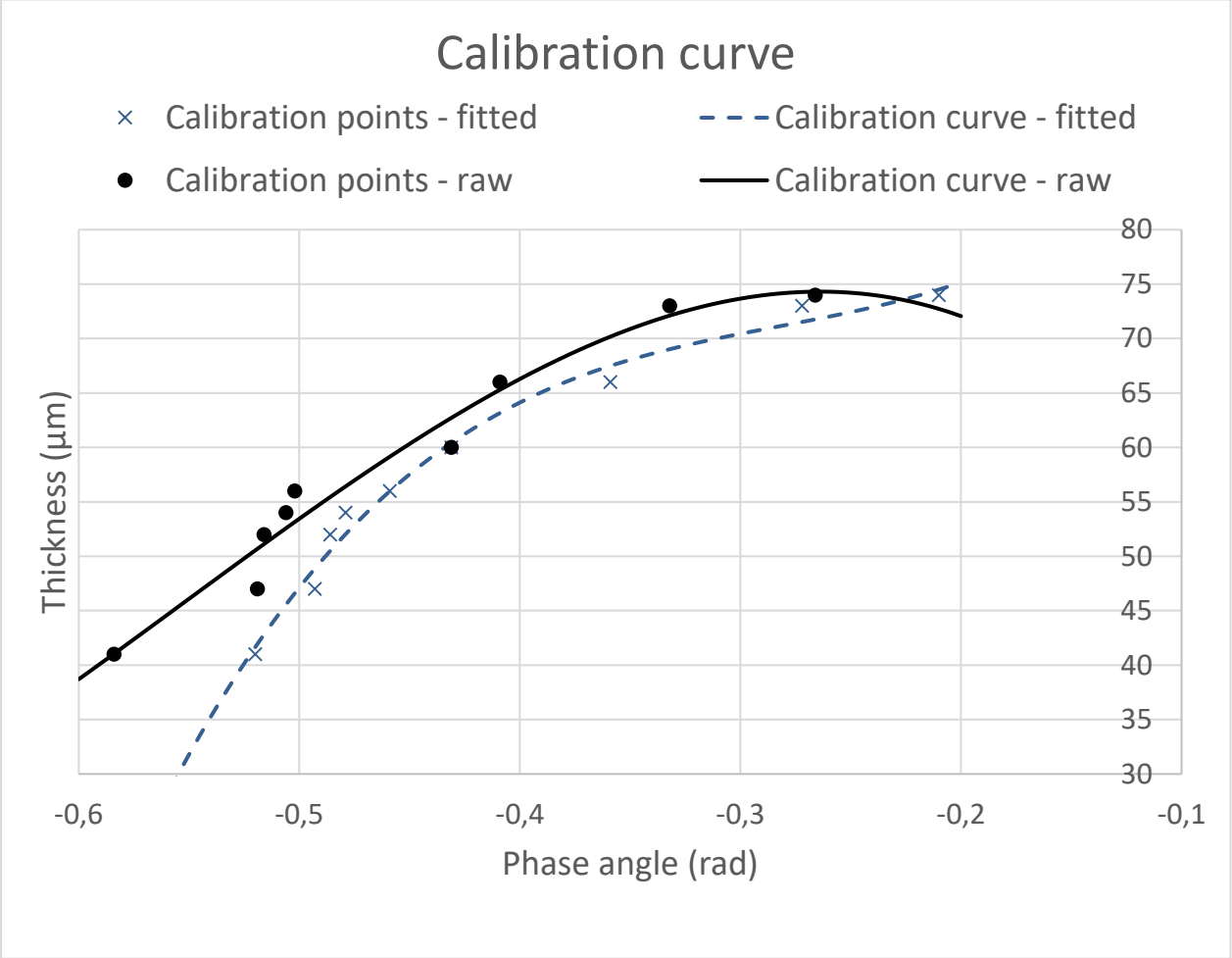

Figure 2. Calibration curve.

Figure 2 shows calibration curves for raw and fitted data. The graph shows good match between measured data (points in the graph) and calibration curves (obtained via equation 2, with constants C_1-C_4 for raw data -590.8, -981.5, -394.6, 27.67 and for fitted data 1515, 1284, 401.4, 116.2). The curves were valid for interval 41-74 µm. The dependency of phase angle on thickness cannot be predicted out of this interval because the functions were designed just for the inside of this region. We can see this effect on the calibration curve obtained from raw data, where phase went down after reaching 74 µm but in reality it should continue to grow. It should be pointed out, that more data for calibration can provide better determination of thickness. Different functions can be also used. The important thing is to have as many pairs (phase-thickness) as possible for the precise fit. The phase values for fitted and raw data differed for the same thicknesses. This was caused by noise suppression.

Phase images were converted via calibration curve (equation 2 with corresponding constants) to images of paint thickness. Thickness maps based on phase images are shown in figure 3. Results obtained from raw data and fitted data showed approximately the same thickness. Nonetheless the raw data were little bit noisier.

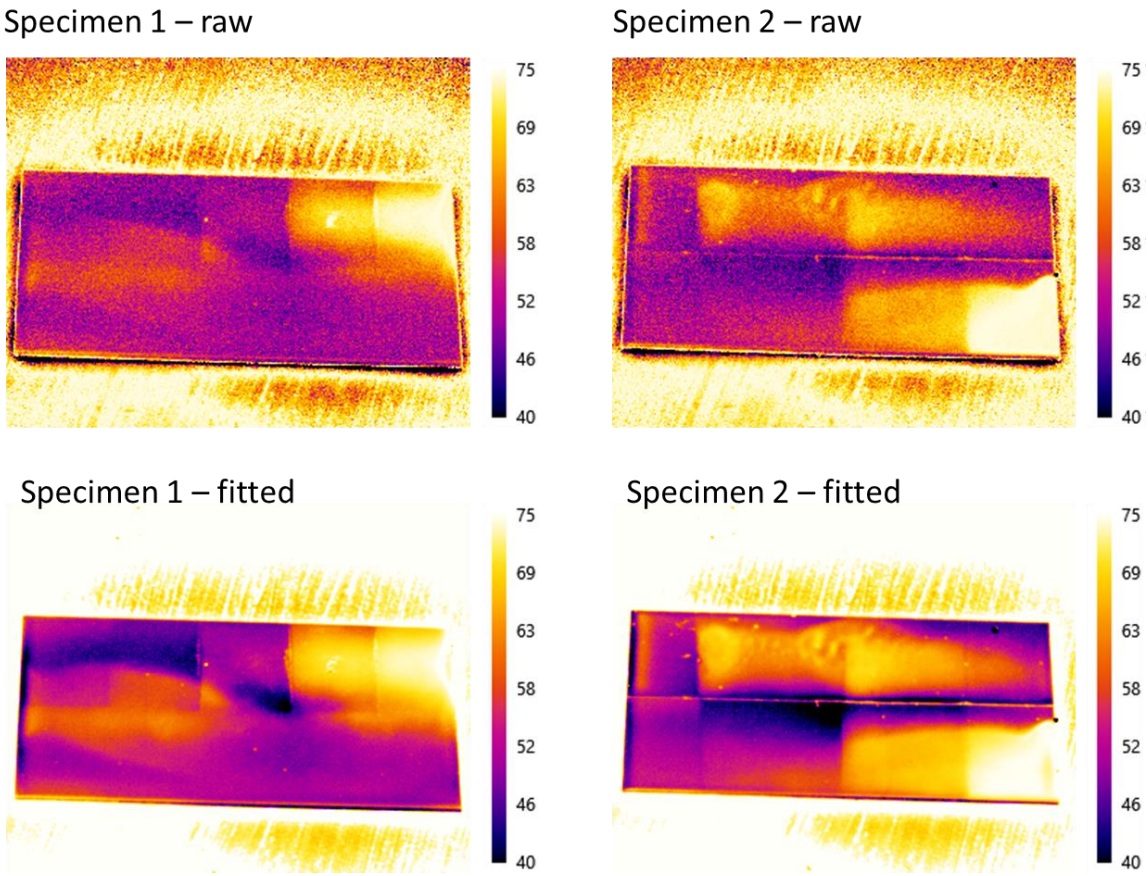

Figure 3. Results, the range is in μm.

For determination how well the thickness was estimated, both specimens were measured with thickness meter. Specimens were divided in ten zones from which the average thickness was measured. Nine measurements were performed in each zone (3 x in the top part,3 x in the middle and 3 x in the bottom part). The zones can be seen in figure 4. Correspondingly, the average of the zones was obtained from those zones from results by PPT.

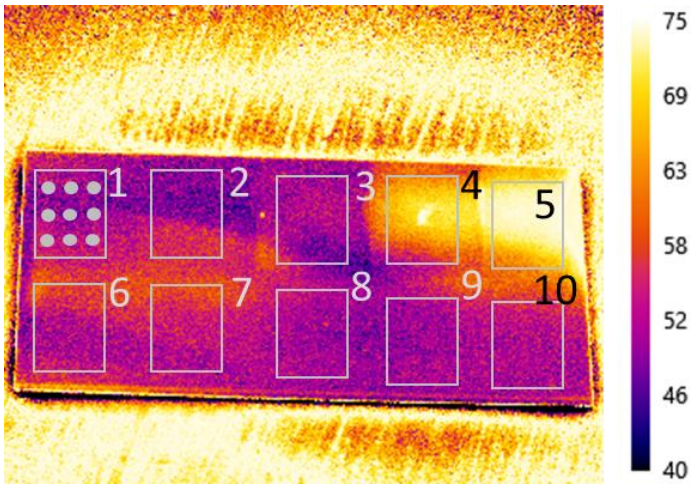

Figure 4. Placement of zones, white dots in zone 1 represents points of measurement.

The results are in table 3. Thickness determination for specimen 1 was worse than for specimen 2. Average relative error for specimen 1 for raw data was 4.9 % for fitted data 4.3 % and for specimen 2 for raw data 3.6 % and for fitted data 2.8 %. As expected with fitted data we obtained more precise results. The difference was not big but for some application it can be crucial. We expected that the thickness estimation would be better for sample on which the calibration (specimen 1) was performed but that was not confirmed. The probable cause for that was that non-uniform heating influenced phase values in the center of the lamp (zone 3 and 8) due to higher energy (energy was the biggest in the center of the lamp). Those phase values were slightly shifted and therefore the thickness differed. This was especially problem for specimen 1 in the zone around the center of the lamp due to steep calibration curve around 56 μm. Specimen 2 had thickness around 65 μm in the center of the lamp and the effect of a non-uniform heating was masked due to not that steep calibration curve around this thickness. Basically the thickness was less phase sensitive around 65 μm. We should point out that even with highest relative error 8.9 % the absolute thickness difference between measured thickness by thickness meter and estimated by PPT was less than 6 μm, which is acceptable for many of industrial applications.

Table 3. Results of estimated thicknesses

	Specimen 1										
	Zone	1	2	3	4	5	6	7	8	9	10
Average thickness from the zone (um)	Thickness meter	47	52	56	67	73	52	55	56	55	54
	FFT phase raw	51	51	51	65	71	53	54	51	51	52
	FFT phase fitted	49	50	51	66	71	53	56	52	51	52
Relative error (%)	FFT phase raw	8.5	1.9	8.9	3.0	2.7	1.9	1.8	8.9	7.3	3.7
	FFT phase fitted	4.3	3.8	8.9	1.5	2.7	1.9	1.8	7.1	7.3	3.7
	Specimen 2										
	Zone	1	2	3	4	5	6	7	8	9	10
Average thickness from the zone (um)	Thickness meter	54	64	65	60	56	48	51	64	65	74
	FFT phase raw	52	59	63	58	53	51	51	61	65	73
	FFT phase fitted	52	61	65	59	53	51	51	62	66	73
Relative error (%)	FFT phase raw	3.7	7.8	3.1	3.3	5.4	6.3	0.0	4.7	0.0	1.4
	FFT phase fitted	3.7	4.7	0.0	1.7	5.4	6.3	0.0	3.1	1.5	1.4

5 Conclusion

Flash pulse phase thermography measurement was used for the paint thickness estimation on AISI 304 substrate. The thickness was determined from phases via the calibration curve thickness-phase with satisfactory results. The average relative error was less than 3.6 %. The maximum difference between the thickness measured by the standard thickness meter and obtained with PPT was less than 6 μm in thickness range from 41 to 74 μm. It should be pointed out that the thickness obtained and thus the measurement error with PPT greatly depends on the calibration curve, which is also a big disadvantage of the measurement procedure. The calibration curve depends on phase values, which can differ for example due to used energy, energy distribution of a lamp, distance between a lamp and a specimen, a used paint. Therefore, when phase values changes due to a measurement setup, calibration curve has to be redetermined. That means that calibration curve is valid for a fixed measurement setup. The calibration curve doesn't have a linear characteristic and therefore thickness sensitivity and thus relative error can differ in different thickness ranges. The effect of non-uniform heating can negatively influence the precision of thickness determination. This effect was negligible for the tested samples. The biggest

advantage is in the speed of the measurement. Thickness values of whole samples (100 x 50 mm) were measured in 4 s, which corresponded to the measurement time of two points by a standard thickness meter. Another advantage is that the measurement is non-contact and therefore no surface damage can be induced (cracks, indents, etc.). The results suggest that flash pulse phase thermography could be a viable tool for an estimation of a paint thickness on planar parts with a high speed.

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