NEAR INFRARED IMAGING FOR MEASURING RESIN THICKNESS ON COMPOSITES

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ABSTRACT

Excess resin on the surface of composite structural materials can affect performance of the underlying structure. One example is a resin filled pocket in a surface wrinkle in cured composite. Even if the wrinkle is visible, it is not currently possible to determine its depth non-destructively. In other cases, excess resin on the composite surface might result from a wrinkle in the bagging material, so there is no underlying composite feature. NDI methods based on ultrasound can detect resin pockets in excess of 0.040 inches (40 mils) deep but cannot accurately measure their depth. Until now there has been no reliable method for detecting resin pockets in the 5 to 40 mil range. Near Infrared (NIR) imaging can accurately measure surface resin on composite materials from 2 to 75 mils thick, detecting virtually all resin pockets, resin filled surface wrinkles and other surface resin features. NIR imaging can measure resin feature location, width, length and the structually important width/depth ratio.

1. INTRODUCTION

Infrared spectroscopy has been used for composite NDI in the recent past because it can measure the chemistry and condition of the resins used in epoxy matrix composite materials.[1] Mid infrared spectroscopy, in the 2.5 to 20 micrometer range, gives valuable chemical information on thin resin layers on the surface of composites. If one uses the near infrared spectral information in the 900 to 1700 nm range, the absorbance bands for epoxy materials are very low amplitude compared to the mid infrared range and it is possible to quantitatively measure the depth of resin features in the 0.005 to 0.075 inch (0.125-1.875 mm) range. Using an imaging method in the near IR range, it is possible to precisely measure epoxy resin depth on broad areas of composite part surfaces.

Hyperspectral imaging refers to methods that use many spectral bands to create useful information about a measurement scene of interest. Hyperspectral imaging in the near IR (NIR) ranges has been used for aerial surveillance, crop information and battlefield scene intelligence among other applications. Hyperspectral remote sensing was originally developed for mining and geology (the ability of hyperspectral imaging to identify various minerals makes it ideal for the mining and oil industries, where it can be used to look for specific ores or traces of oil)[2]

1.1 Overview

New NIR hyperspectral imaging apparatus and methods were developed to detect resin features on the surface of carbon fiber composites. A "push broom" hyperspectral imaging approach refers to a method where a line of pixels is measured and moved along a path that is perpendicular to the pixel line. The push-broom approach to imaging is capable of high spatial resolution to define the length, width, and depth of the resin features. In the past such features could only be detected if they were over 0.040 inches (40 mils) thick, and required operating ultrasound equipment at a very slow speed. The NIR imaging apparatus was operated at speeds of 15 feet/min to cover areas up to 40 feet in length. The measurement can be reported as defect reports that list the position, length, width and depth of resin-rich features; or depth images in 2D or 3D format. The hyperspectral method is more easily applicable to unusual geometries than ultrasound, because optical methods do not require intimate contact with the part.

2. EXPERIMENTATION

2.1 NIR hyperspectral imaging technology overview

Hyperspectral imaging (HSI), or chemical imaging (CI), is the combination of spectroscopy and digital imaging. A hyperspectral image contains many spectra, one for each individual point on the sample's surface. The image contains valuable information about the spatial distribution of the materials, as well as chemical and physical characteristics of the sample. A hyperspectral camera is the integration of an imaging spectrograph with a matrix array sensor. See Figure 1.

Figure 1 Simplified push-broom hyperspectral camera components diagram.

A special lens images the sample onto a slit of a transmission spectrograph. The spectrograph produces a spectrum imaged on a focal plane array detector, preserving the location of respective points on the slit and thus the points of the line on the sample. In push-broom HSI, successive lines on the sample measured over time form a complete hyperspectral (HS) dataset. This data from a HSI camera is called a "hypercube", containing information in two spatial dimensions and one spectral dimension. The hypercube is typically ratioed with similar hypercube measurements of a highly reflective white reference material and the residual background signal, the latter of which is measured when no light is falling on the focal plane array. The resultant corrected spectra are produced in transmittance, reflectance, or absorbance similar to traditional spectroscopic measurements. Push-broom HS cameras gather a complete spectrum at each point along one spatial line at a time (Hyvärinen, et al., 2007)[3]. The area of the object is scanned, one line at a time in rapid succession. To image the whole sample, either the sample or the camera must move. The hypercube is collected by compiling the optical data from each spatial line.

Since push-broom imaging detects spectra of every point of a line at the same time, the spectral data in the hypercubes correlate with the measured sample point. This is why push-broom HSI cameras are used with the samples moving, which is the case in many manufacturing lines, or scanned over the samples, such as is schematically shown in Figure 2.

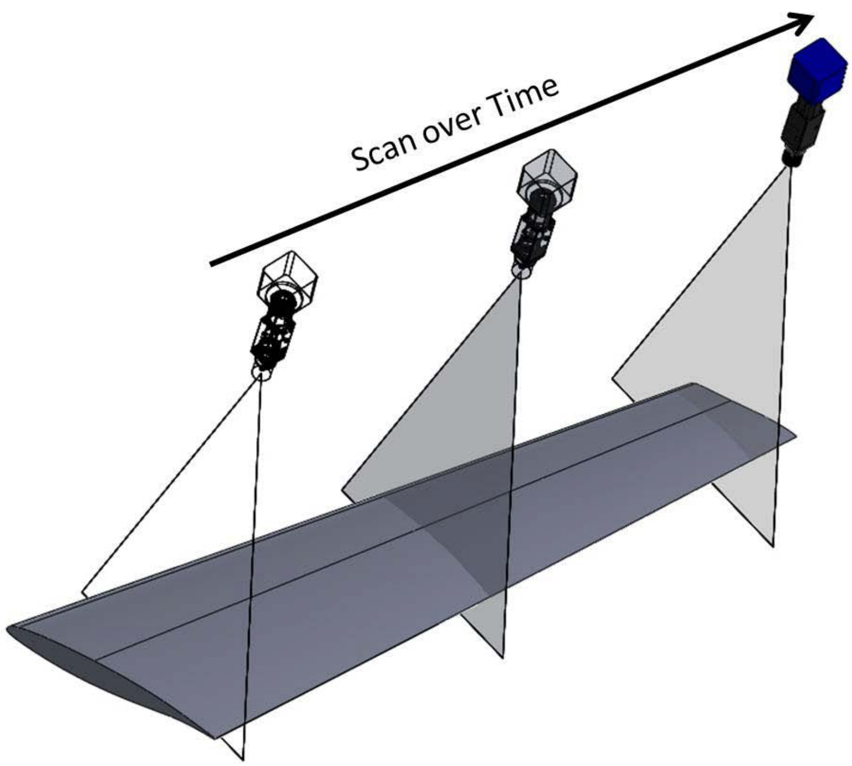

Figure 2 Diagram of the hyperspectral camera scanning over the exterior of a part.

2.2 NIR calibration for resin depth on large composite surfaces

The first application for NIR imaging was a composite structure on which all surfaces had a single outer ply of fiberglass material which gave a typical surface resin thickness on the order of

2 to 3 mils. NIR Hyperspectral imaging is similar to the conventional reflectance spectroscopy with a source illuminating the surface and wavelength selective optics detecting the reflected light. Near-infrared light in the 1000-1700 nanometer (nm) range penetrates the resin and is scattered back from the fiberglass and graphite filaments so that light passes through the resin twice. The double transmission spectra have the chemical signature of the resin and the amplitude of the each spectrum is proportional to the resin depth at that point. Resin thickness standards on a substrate that mimics the structure to be measured were made to calibrate the system for resin depth. Figure 3 shows typical reflectance spectra obtained on resin standards with different thicknesses that were made on coupons to mimic the composite structure surface.

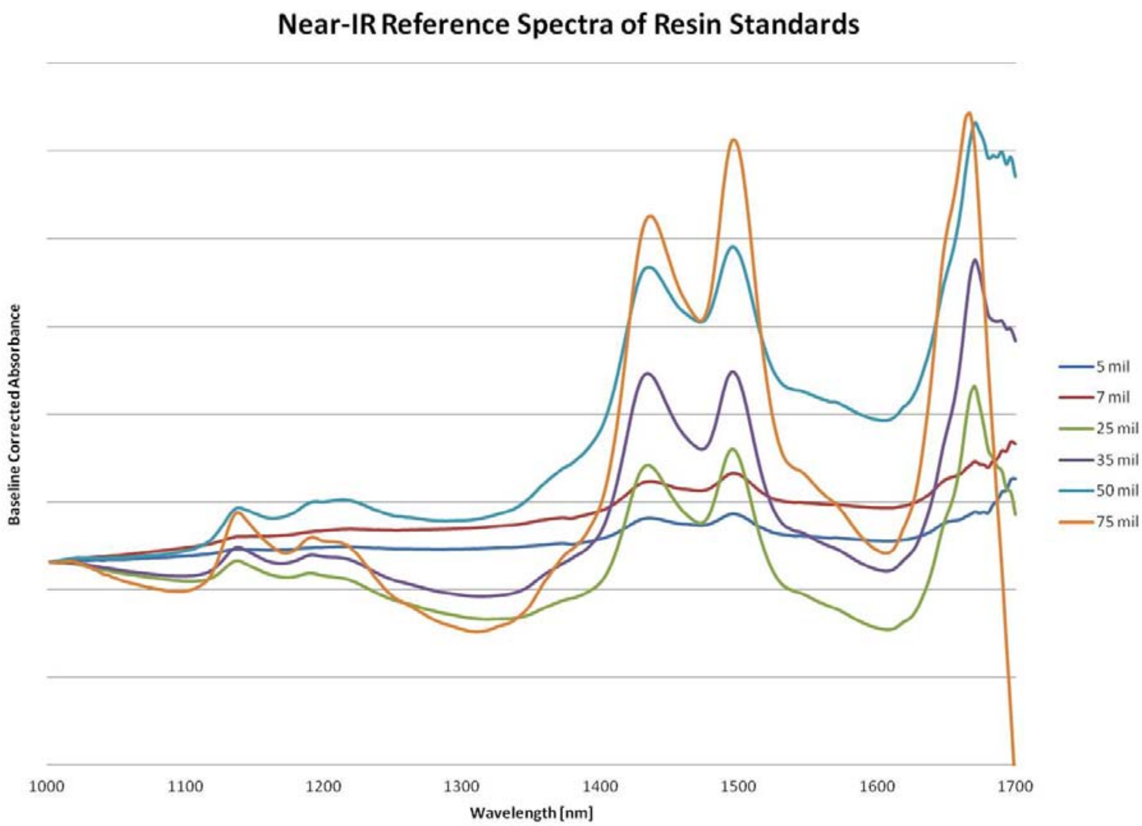

Figure 3 Near infrared spectra (1000 to 1700 nanometer range) for a range of epoxy resin thickness standards (spectra were normalized at 1000 nm for comparison).

A variety of factors can affect baseline and general shape of the near IR spectra. The most important factor is resin depth, but the surface finish on the resin, underlying fiber orientation, and the shape of the part being measured can be additional factors. The epoxy resin thickness standards shown in Figure 3 have a carefully controlled surface finish but the underlying substrates may not have been well matched. Chemometric data processing methods are used to represent the complex relationship between the spectra and the resin thickness and provide the correlation to predict point-by-point the local resin thickness and thus produce thickness maps of the scanned surface.

2.3 NIR hyperspectral imaging equipment

The NIR hyperspectral imaging equipment currently in use at Boeing is model MCR-920-100-01 from Middleton Research in Middleton, Wisconsin. This equipment includes a measurement instrument with wheels to allow it to crawl into a large composite structure and measure resin as it travels. Standards to calibrate the systems were made at Boeing and both the standards and the equipment were certified by Boeing metrology. This was necessary in order to allow measurements of production parts with the equipment. Software to perform data collection and a separate software package for data analysis were provided by Middleton Research with the equipment.

2.4 Hardware and operation for NIR hyperspectral imaging system

NIR hyperspectral imaging resin depth measurements are made in the radii in both the upper skin and lower skin on large composite parts. The MCR-920-100-01 NIR measurement head is shown in Figure 4 with measurement head and equipment cart performing a resin depth measurement in the radius of a test article. The NIR imaging measurements are done with coordinated hardware and software operations. The NIR measurements for larger parts require two operators with one handling the software and start up sequence and the other handling the measurement head and cable.

Figure 4 Operator running the NIR measurement on one of the outer radii on a composite test article.

2.4.1 Software for NIR hyperspectral imaging system

There are two software packages for the NIR hyperspectral imaging system. One package is for all data collection operations and the other is for post processing the collected data. The data collection software has functions for data collection for references and resin thickness standards and different functions for live data collection for resin thickness on composite parts. The post processing software package (Thickness software) has functions for generating a new calibration using data from resin thickness standards. It also has multiple functions for reviewing and reporting the measured resin thickness on composite parts.

2.4.2 Calibration standards and calibration software

2.4.2.1 Calibration standards

In order to calibrate and certify the hyperspectral equipment, a set of resin thickness standards were prepared. The standards ranged from 5 to 75 mils thick and were certified with edge readings made on a NIST traceable visible microscope. A resin thickness calibration procedure was written for the NIR hyperspectral imaging system in order to standardize a metrology procedure for calibrating and certifying the system.

The NIR optical equipment wavelength range was independently calibrated to a Model 1920x NIST Traceable Near Infrared Wavelength Standard (Middleton Research, Middleton, WI) and also tested for linearity using a Sealed Near Infrared Linearity Set (Middleton Research, Middleton, WI).

2.4.2.2 Calibration software

The data for calibrating the NIR system is collected while the measurement head is in its cart. A drawer allows the operator to slide reference materials into the proper measurement position and orientation. The data collection software is used to collect the raw calibration data for references and standards. The calibration to resin thickness first requires the operator to import the raw reference data into the calibration software. The raw data for the resin standards is imported next. The calibration software has functions to view and select the most useful areas on the raw data fields for references and standards to give the best calibration possible.

The calibration can be saved and called up by the operation software so the operator can see a real time display of the resin thickness while doing the data collection. Figure 5 shows an example displayed on the Calibration panel in the Thickness software. This calibration used multiple readings on each of 6 thickness standards and had an R^2 value of 0.962.

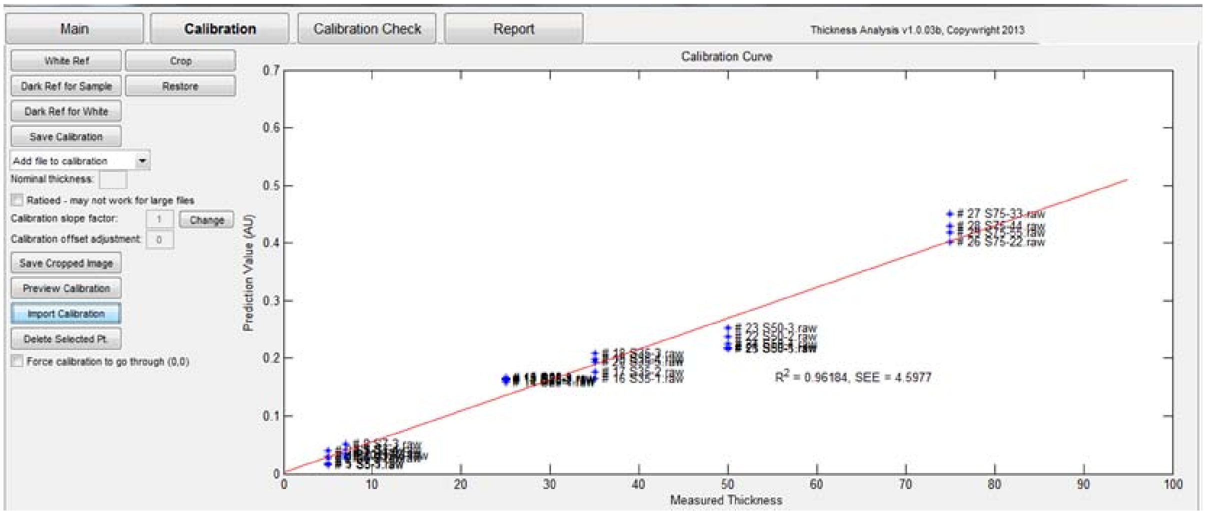

Figure 5 Example resin thickness calibration in the Thickness software.

2.4.3 NIR Inspection data collection software

The NIR data collection software allows the operator to identify the part being measured, identify the radius being measured and initiate data collection. It has a function to call up a resin thickness calibration so the real time display during data collection is referenced to a good resin depth calibration. It also allows the operator to turn on a video camera that displays a real time image of the area being measured by the NIR system. Figure 6 shows the operation software during a data collection sequence. The video images were used to verify that resin features are not protruding from the surface.

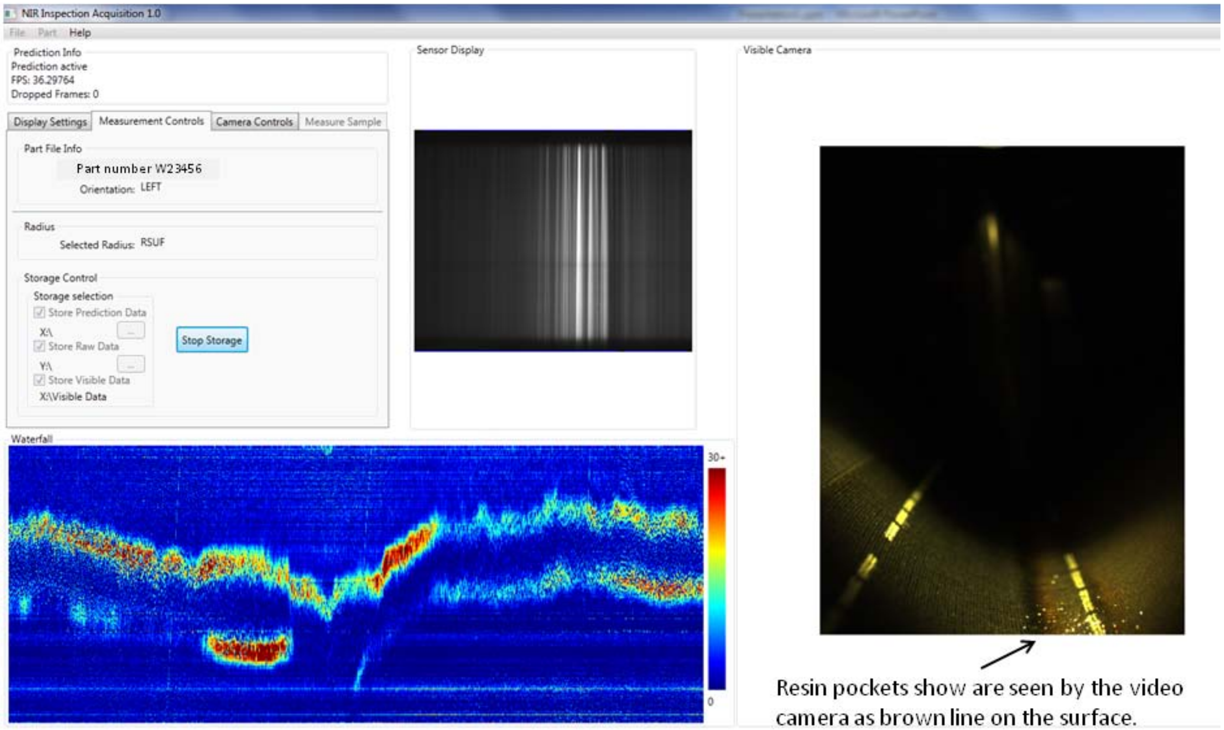

Figure 6 Data collection and live-display software. This image shows a series of surface resin pockets in the NIR image and a visible resin feature on the surface in the video image.

2.4.4 Data post processing software

The data post-processing software was used to generate the calibrations to predict resin thickness from raw NIR data. The resin thickness reporting functions include the ability to generate a defect report with the operator hand selecting the defects, cross sectional thickness profiles, and resin pocket images. The defect reports include many details for each resin pocket that is deep enough to be identified as a defect, including length, depth, width, and the ratio of width to depth.

The radii measurements for a single production part may be imported to mark defect locations on each one. The user scrolls through the predicted thickness image and can also view corresponding visible camera images. After analyzing radii measurements, the operator can generate a defect report in Excel tabulating the defects, their location in the radius of the part, the distance along the length of the part, depth readings, and other values. Figure 7 shows one of the data post processing functions in the Thickness software package.

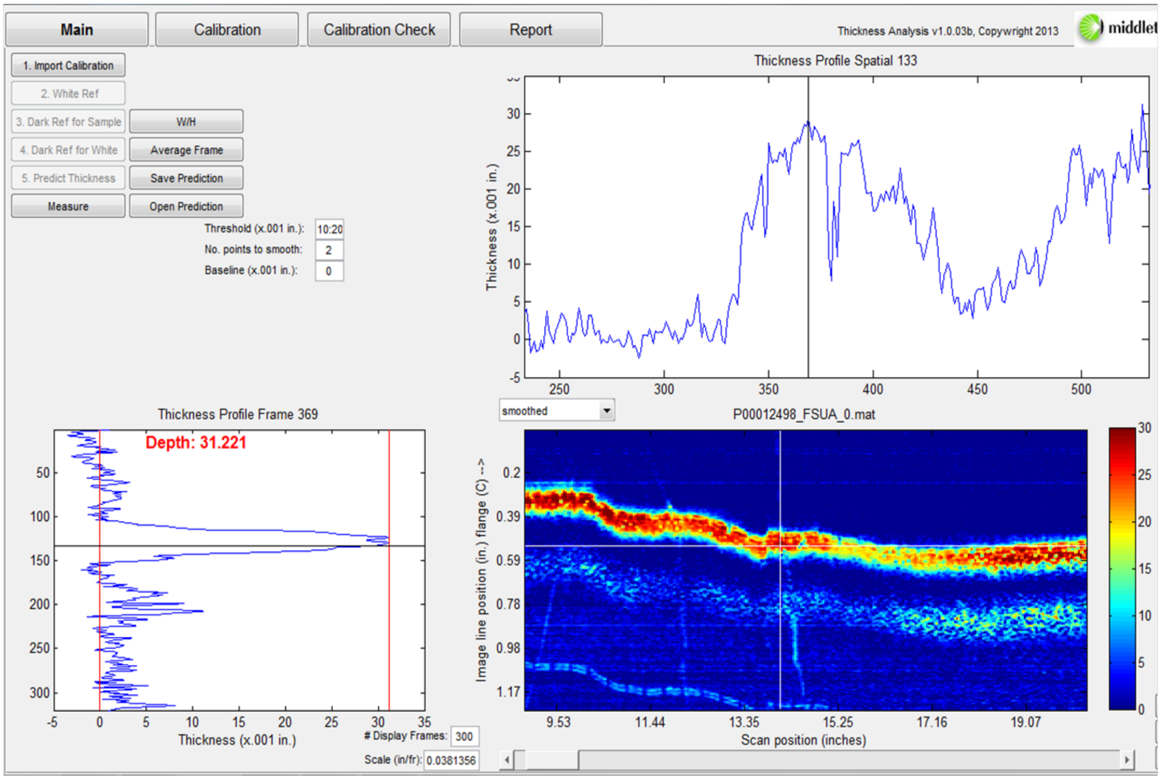

Figure 7 shows one data post-processing example screen.

3. RESULTS

3.1 Example NIR data from test articles

The NIR data presented below was made with the NIR prototype system. Qualification tests of the two capital equipment systems purchased to date show good resin thickness correlation between those systems and the prototype on the same production parts. The data shown in this paper is from composite test articles and not production parts. Both capital equipment systems and the original prototype are now being used to measure production parts for Boeing.

3.1.1 NIR defect report example

An example of the NIR defect map shows many different metrics for each resin pocket selected. The NDI operator must decide which resin pockets are severe enough to be considered a defect and also selects the starting and end point of the resin pocket and the width of the resin pocket. Figure 8 shows an example defect map from a test article. The defect report is saved in a standard Excel format which makes it easy to read by others who do not have the NIR software.

As noted above there are several additional formats available for reporting resin pocket defects found with the NIR system. The defect report exported to Excel is one of the most commonly used report formats and it is available with the defect images for each reported defect.

Item	part	Area	Fwd/Aft	Defect Type	Start to defect (in)	Width (in)	Depth (mils)	Length (in)	W/D ratio
1	upper	T1	aft	pocket	21.5	0.21	38.7	22	6.37 (at 36.1in.)
2	upper	T1	aft	pocket	46.7	0.25	35.6	13.6	7.02 (at 59.1in.)
3	upper	T1	aft	pocket	61.9	0.18	51.9	21.1	3.52 (at 66.9in.)
4	upper	T1	aft	pocket	85.9	0.27	27.6	4.5	9.93 (at 89.8in.)
5	upper	T1	aft	pocket	98.6	0.4	39	30	10.29 (at 113.4in.)
6	upper	T1	aft	pocket	139.5	0.18	34	20.2	5.4 (at 144.7in.)
7	upper	T1	aft	pocket	164.5	0.3	29.5	26.6	10.17 (at 171.7in.)
8	upper	T1	fwd	pocket	29.1	0.36	25.6	17.8	13.97 (at 30.4in.)
9	upper	T1	fwd	pocket	60.1	0.37	23.7	13.4	15.73 (at 62.2in.)
10	upper	T1	fwd	pocket	82.9	0.8	23.8	13.9	33.77 (at 83.7in.)
11	upper	T1	fwd	pocket	376.1	0.15	22.4	2.7	6.58 (at 377.2in.)
12	upper	M1	aft	pocket	58.3	0.3	24.2	4.8	12.55 (at 61.6in.)
13	upper	M1	aft	pocket	77.3	0.14	41.3	27	3.4 (at 84.9in.)
14	upper	M1	aft	pocket	112.2	0.15	36.7	34.2	4.1 (at 121.1in.)
15	upper	M1	aft	pocket	153.5	0.28	35.2	21	7.89 (at 166.6in.)
16	upper	M1	aft	pocket	178.6	0.18	27.9	25.3	6.34 (at 196.2in.)
17	upper	M1	aft	pocket	210.3	0.64	21.9	35	29.34 (at 234.4in.)
18	upper	M1	fwd	pocket	32	0.49	35.6	27.4	4.82 (at 42.4in.)
19	upper	M1	fwd	richness	38	0.34	23.1	65.9	14.66 (at 59.3in.)
20	upper	M1	fwd	pocket	61.8	0.39	31.2	17.5	12.39 (at 71.7in.)
21	upper	M1	fwd	pocket	98.5	0.34	26	15.6	12.95 (at 107.6in.)
22	upper	M1	fwd	pocket	143.8	0.11	19.6	4.5	5.81 (at 147in.)
23	upper	M1	fwd	pocket	211.8	0.14	23.1	15.4	6.04 (at 223.8in.)

Figure 8 Example NIR defect map. Resin pockets deeper than 30 mils are highlighted with a red resin depth number.

4. CONCLUSIONS

The NIR hyperspectral imaging systems are very effective for detection and measurement of resin pockets in composite structures. NIR hyperspectral imaging for resin depth measurement has proven to be accurate to +/- 0.005 inches of resin depth in the 0.005 to 0.075 mil resin depth range. This method is in production use at two different composite manufacturing facilities for composite parts with very different geometries and measurement situations. Additional applications for the NIR hyperspectral imaging system are being tested and evaluated. It is likely that this technology will be used in other composite manufacturing situations with appropriate modifications to deliver the NIR hyperspectral imaging measurements to composite parts with a variety of different geometries.

Boeing holds significant intellectual property in the area of infrared and near infrared measurements to support thickness measurements.[4-8] The Boeing intellectual property for NIR hyperspectral imaging is licensed to Middleton Research to provide NIR systems for other composite manufacturing companies.

5. REFERENCES

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