NONDESTRUCTIVE EVALUATION OF THERMAL SPRAY COATING INTERFACE QUALITY BY EDDY CURRENT METHOD

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Abstract. Thermal spray coating is usually applied through directing molten or softened particles at very high velocities onto a substrate. An eddy current non-destructive inspection technique is presented here for thermal spray coating interface quality characterization. Several high-velocity-oxy-fuel (HVOF) coated steel plates were produced with various surface preparation conditions or spray process parameters. A quad-frequency eddy current probe was used to manually scan over the coating surface to evaluate the bonding quality. Experimental results show that different surface preparation conditions and varied process parameters can be successfully differentiated by the impedance value observed from the eddy current probe. The measurement is fairly robust and consistent. This non-contact, nondestructive, easy-to-use technique has the potential for evaluating the coating quality immediately after its application so that any defects can be corrected immediately.

INTRODUCTION

Thermal spray coating is defined as a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semi-molten condition on a prepared substrate to form a sprayed deposit [1]. Thermal spray coatings have been used in all major sectors of the marine and industrial corrosion control coatings market for many years. It also has a very large market in the restoration or machine element repair industry. Components that can be repaired by this process include, but not limited to, shafts, impellers, bearing surfaces, turbine blades [2], pump housings etc. In recent years, there has been an increasing need to incorporate coatings as part of the component design and not as a "repair" or "afterthought" overlay [3].

Many factors affect the thermal spray coating interface quality. The most apparent factor is the substrate surface preparation [4]. Cleaning and grit blasting provide a chemically and physically active surface needed for good bonding. The increased surface area and roughness resulting from the surface preparation process promote mechanical keying and increase the coating bond strength. Other affecting factors include various process parameters such as spray angle, spray nozzle distance etc. Those process parameters affect the thermal and kinetic energy of the sprayed particles. Increase in thermal and kinetic energy increases chances of mechanical bonding.

Coatings usually have poor strength, ductility and impact properties. Theses properties tend to be dictated by the weakest link in the chain which in coatings tends to be the particle or grain boundaries and coating/substrate interface. While techniques have been developed to monitor the spray coating process for the process control and quality optimization [5], defects may still occur at the manufacturing process or during the service period. So there is a need for nondestructive evaluation or inspection of the thermal spray coatings. So far there are very few reliable NDE methods available for thermally sprayed coatings. The majority of tests for coatings tend to be destructive in nature such as epoxy pulling test. Eddy current method has been used to measure the thickness of the thermal spray coating to estimate its quality [6]. Generally speaking, ultrasonic and magnetic particle flaw detection methods have been proved to be poor with thermally sprayed coatings since the vast number of particle boundaries give flaw like responses and cause high levels of interference. Advanced techniques like thermography, thermal wave interferometry [7] and acoustic emission are presently being researched and are still in laboratory setups with limited practical use for industry.

In this paper we present an eddy current technique for characterizing the thermal spray coating interface quality. Several HVOF coated steel plates were produced with various surface preparation conditions, e.g., grit-blasted surface, wire-brush cleaned surface, and a dirty surface, and different spray process parameters such as spray angle, spray nozzle distance etc. A quad-frequency eddy current probe was used to manually scan over the coating surface to evaluate the bonding quality. Blind experimental test results agree quite well with the ground truth and show that the coating defects caused by the dirty surface or varied process parameters can be successfully differentiated by the impedance value observed from the eddy current probe.

EXPERIMENTAL SETUP

A computer based eddy current inspection system offered by a German company IZFP was used for this study. The system is mainly composed of an instrumentation board designed for PC-aided eddy current testing and a quad-frequency eddy current probe. The connection between the eddy current board and a PC is realized through an Ethernet network interface, which provides easier and faster data transferring than other interfaces. The modular design of this PC based eddy current system makes it easy to build a customized inspection system that features automatic scanning and advanced signal processing capabilities. The overall system setup is shown in FIGURE 1. The eddy current board is packaged in the gray box shown in the right.

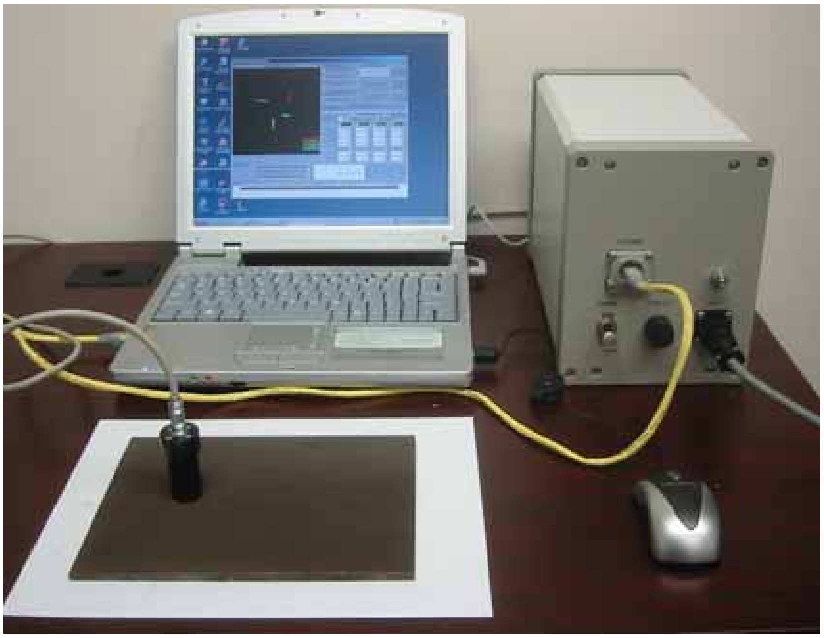


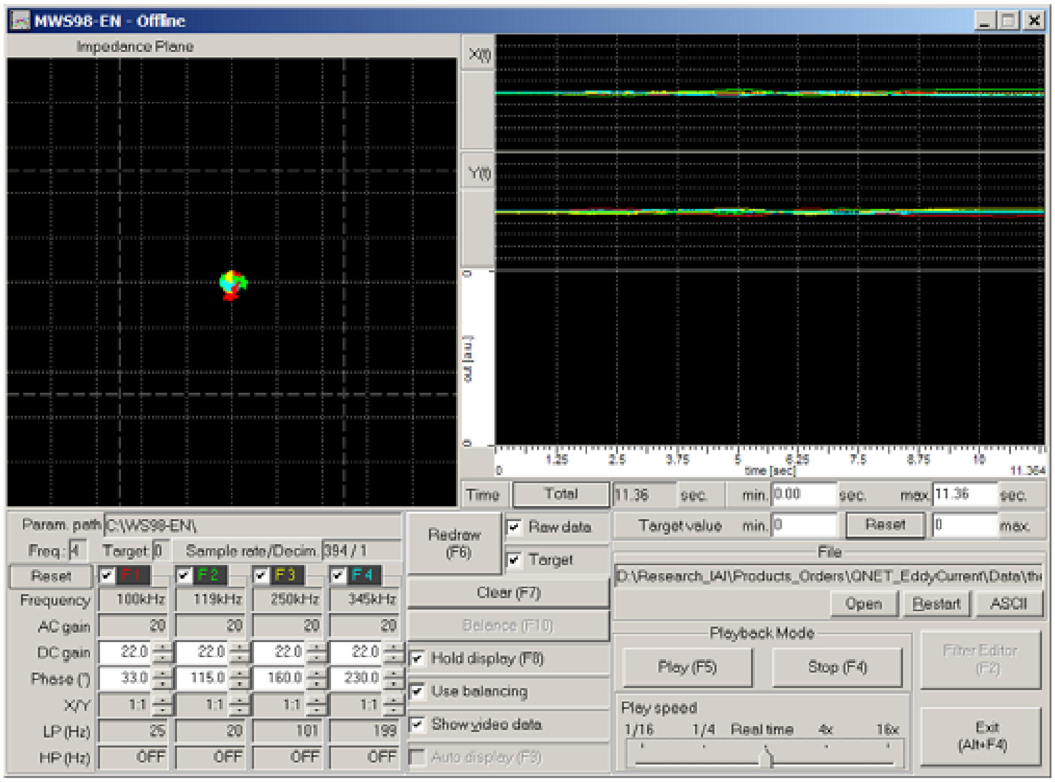
FIGURE 1. The eddy current system used to inspect the thermal spray coating.

EXPERIMENTAL RESULTS AND ANALYSIS

Eddy Current Results Interpretation

The basic output of the eddy current system is a complex impedance value measured by the eddy current probe. The impedance value is usually affected by several parameters, such as probe lift-off distance, inspection frequency, material conductivity, and the presence of defects on or near the object surface, etc.

The impedance value can be displayed in an impedance plane to show its trace when certain parameter is varied, such as the lift off, location of the probe, etc. It can also be displayed as two time-domain curves which show how the real and the imaginary part of the impedance value vary over time. An example is shown in FIGURE 2 where the impedance plane is displayed on the left and the time based plots are displayed on the right. The eddy current system runs on four frequencies simultaneously and the results from the four frequencies are represented with four different colors.



Param. path: C:\WS98-EN\
Freq.: 4 Target: 0 Sample rate/Decim. 394 / 1

	☑ F1	☑ F2	☑ F3	☑ F4
Frequency	100kHz	119kHz	250kHz	345kHz
AC gain	20	20	20	20
DC gain	22.0	22.0	22.0	22.0
Phase (°)	33.0	115.0	160.0	230.0
X/Y	1:1	1:1	1:1	1:1
LP (Hz)	25	20	101	199
HP (Hz)	OFF	OFF	OFF	OFF

☑ Raw data
☑ Target
☑ Hold display (F8)
☑ Use balancing
☑ Show video data
☐ Auto display (F3)

Time Total 11.36 sec. min. 0.00 sec. max 11.36 sec.
Target value min. 0 max. 0
File: D:\Research_IAI\Products_Orders\QNET_EddyCurrent\Data\th

FIGURE 2. Screen shot of the eddy current inspection application software.

Thermal-Spray Coated Specimen with Various Surface Preparation

A 6" x 8" steel plate was thermal-spray coated with HVOF process. To produce different bonding strength quality, the steel surface was divided into three sections and various surface preparations were conducted before the coating process, as shown in FIGURE 4. It is expected that the surface with grit-100 blasting produces the best interface bonding quality, the wire brush cleaned surface produces weaker but still acceptable interface quality and the dirty surfaces produces the worst interface quality.

A piece of copy paper was placed between the coating surface and the probe for protecting the probe. Eddy current output is a relative measurement and it is balanced at the good coating surface (100 grit blasting surface). FIGURE 4 shows the eddy current measurement results when the probe was scanned all over the three regions. The three regions can be clearly differentiated at the impedance plane results.

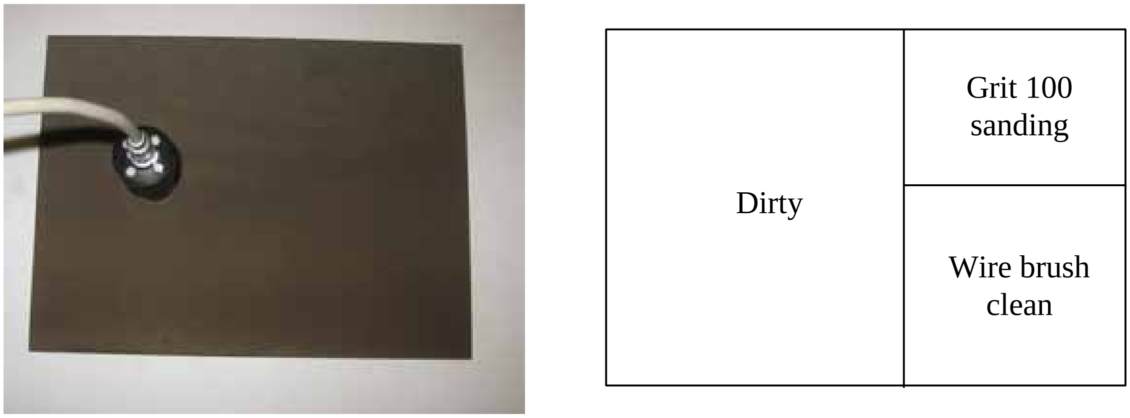


FIGURE 3. Thermally spray coated steel sample with three sections of surface preparation.

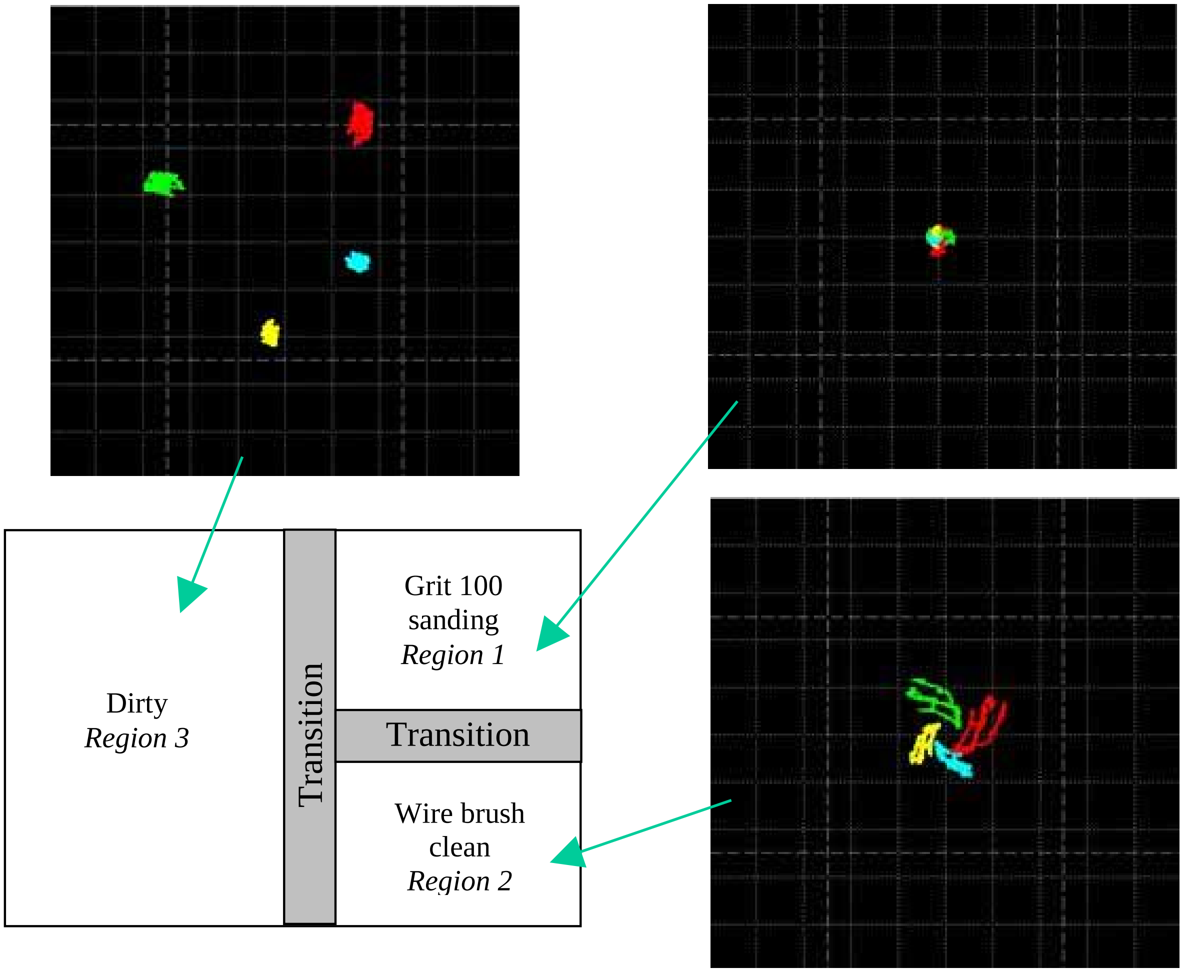


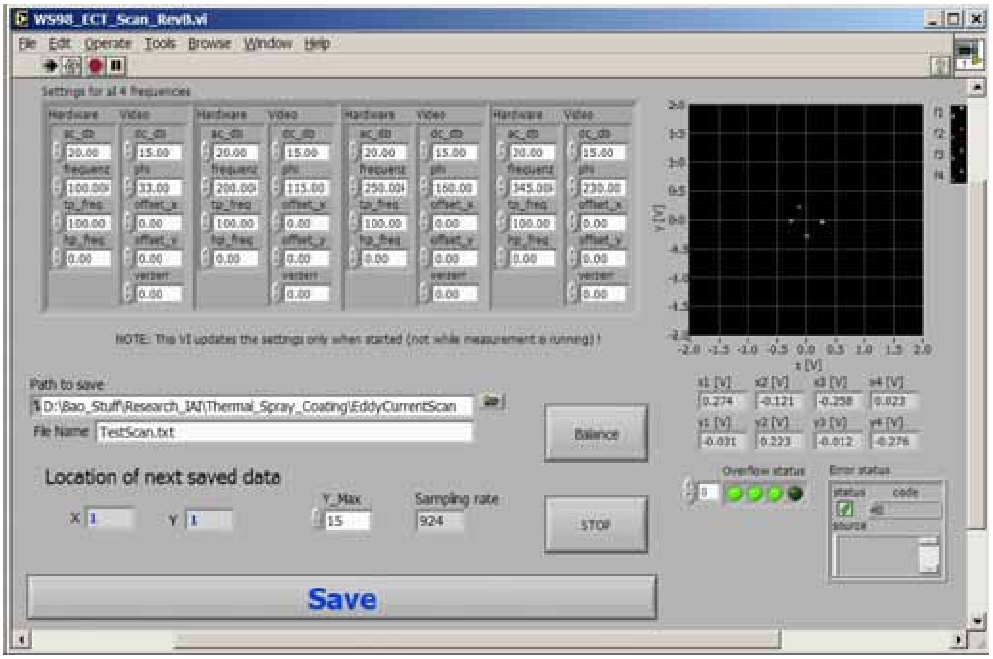
FIGURE 4. Eddy current measurement results for three regions with various substrate surface preparations.

More Specimens for Manual Eddy Current Scanning

Four more thermal-spray coated steel specimens were prepared. These specimens measure 12" x 6" x ¼" and they are with various coating defects introduced by changing the process parameters while producing the coatings.

FIGURE 5. Thermal spray coated steel specimen (12" x 6" x ¼").

2D scans were performed manually to carry out the eddy current inspection on these specimens. A LabVIEW program was written for facilitating the manual scanning process. The GUI interface is shown in FIGURE 6. Since the scan was manually performed, a piece of paper was placed on the thermal spray coating specimens with the grid of probe locations printed on the paper, as shown in FIGURE 7. Two grid pitches were prepared. The coarse resolution is the diameter of the probe which is 0.75", and the fine resolution is half of the probe diameter which is 0.375". Because the purpose of this study is not to locate very small defect in size but rather to prove the concept of using eddy current output to differentiate the differences between the good coating and inferior coating, the relatively coarse resolution should meet the objective. During the scanning process, the probe was manually moved from one spot to the next and the "Save" button on the GUI was clicked so that the complex impedance values of the four frequencies were recorded into a text file. For each specimen, the eddy current system was balanced at the scan starting point, which is the lower left corner of the specimen.



Settings for all 4 frequencies

Hardware	Video	Hardware	Video	Hardware	Video	Hardware	Video
ac_db 20.00	dc_db 15.00	ac_db 20.00	dc_db 15.00	ac_db 20.00	dc_db 15.00	ac_db 20.00	dc_db 15.00
frequenz 100.00	phi 33.00	frequenz 200.00	phi 115.00	frequenz 250.00	phi 160.00	frequenz 345.00	phi 230.00
tp_freq 100.00	offset_x 0.00	tp_freq 100.00	offset_x 0.00	tp_freq 100.00	offset_x 0.00	tp_freq 100.00	offset_x 0.00
hp_freq 0.00	offset_y 0.00	hp_freq 0.00	offset_y 0.00	hp_freq 0.00	offset_y 0.00	hp_freq 0.00	offset_y 0.00
	verzerr 0.00		verzerr 0.00		verzerr 0.00		verzerr 0.00

NOTE: This VI updates the settings only when started (not while measurement is running)!

Path to save: D:\Bao_Stuff\Research_IAI\Thermal_Spray_Coating\EddyCurrentScan

File Name: TestScan.txt

Location of next saved data

X 1 Y 1

Y_Max 15

Sampling rate 924

x1 [V]	x2 [V]	x3 [V]	x4 [V]
0.274	-0.121	-0.258	0.023

y1 [V]	y2 [V]	y3 [V]	y4 [V]
-0.031	0.223	-0.012	-0.276

Overflow status 0

Error status: status ☑ code 0; source

FIGURE 6. LabVIEW program GUI for manual point to point scanning.

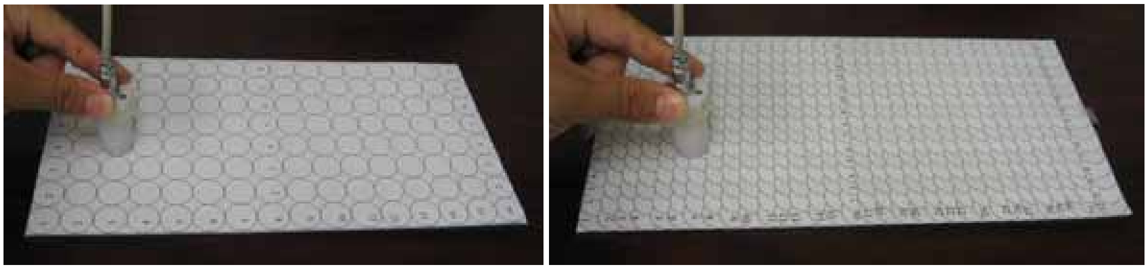

(a) (b)

FIGURE 7. Specimen with a piece of paper attached to the coating surface that shows scanning grids. (a) grid pitch = 0.75" (probe diameter); (b) grid pitch = 0.375" (half the probe diameter).

The eddy current system can handle four frequencies simultaneously. Based on the trial and error results, the frequency range from 100 KHz to 350 KHz is relatively sensitive to the thermal spray coating interface quality even though the designed frequency range for the probe is from 20 KHz to 200 KHz. The following four frequencies were selected for this project: 100 KHz, 200 KHz, 250 KHz, and 345 KHz.

Since the eddy current system output is a complex impedance value for each frequency and contains real and imaginary components, there are eight images produced for all the four frequencies with one scanning. The eddy current output is completely relative and the absolute value can not be used to explain whether there is a defect or not. The goal of this study is to differentiate the areas with good coating quality and the areas with inferior coating quality. Based on the observations of all eight images, some of the images show better differentiations than the others. And among those that show good differentiations, similar patterns were observed. So it is possible to fuse those images with good sensitivity into one image, which bears more reliable information of the coating interface quality.

The following four frequency components were selected for image fusion: 100 KHz imaginary component; 200 KHz real component; 250 KHz imaginary component, and 345 KHz real component. Since the eddy current output is a relative measurement, the sign of the impedance output is not critical. So the first step of the fusion process is to change the signs of the impedance component so that they change in the same direction. Then, all the selected images are added together to be fused into one image.

FIGURE 8 shows the fused images for the four specimens together with the schematic drawing (blue print) that shows how the specimen was prepared. The first two specimens are roughly separated into left and right part from the middle of the specimen, which agrees to the blue print quite well. The third specimen was prepared with three dirty spots. The hot spots shown in the eddy current image are not very obvious except the one at the upper right corner. The fourth specimen has three different kinds of defects, which have their corresponding hot spots in the eddy current image. Note that some of the very hot individual spots were caused by the surface cracking and bulge which increased the eddy current probe lift-off and breaks the eddy current flow in the surface. The measurements at the edge were not very reliable because of the edge geometry.

While a finer automatic scan will produce a better image that shows anomaly in smaller size, the results showed in this report meet the objective of the study. Most of the thermal spray coating interface quality variations caused by varied process parameters can be differentiated. To better understand the results, a careful calibration process is necessary that requires a standard specimen with known coating interface quality.

Measurement Repeatability

To evaluate the measurement repeatability, the same specimen was scanned twice with different resolution. FIGURE 9 presents the comparison between the two scans. It can be seen that the measurements are very repeatable and both the patterns and the relative values are consistent for the two scans.

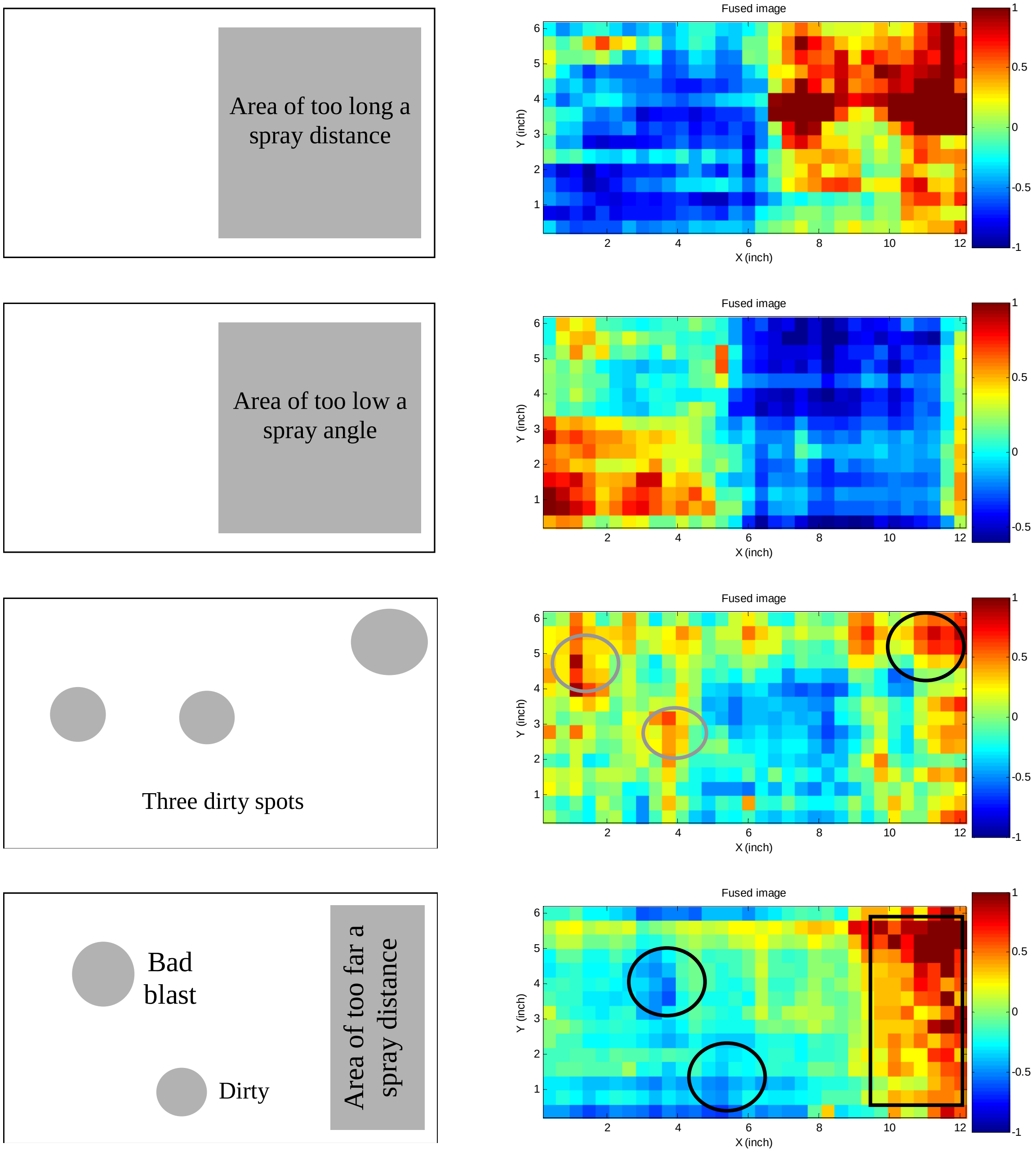


FIGURE 8. Eddy current scan results for four specimens.

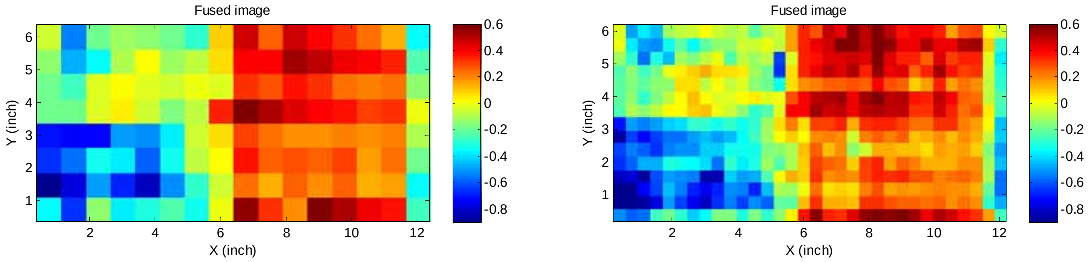


FIGURE 9. Two scan image of the same specimen with different resolutions.

CONCLUSION

Steel specimens with various thermal spray coating interface qualities were tested by the eddy current technique. They were manually scanned and images were produced for each specimen. A simple fusion algorithm was applied to integrate the four-frequency-component images into one image that bears relatively more reliable information of the coating interface quality. Generally the image results agree reasonably well with the specimen preparations even though some measurement noises present. To improve the measurement accuracy and reliability, we are developing a computer controlled 2D scanning system. Much finer images will be obtained and image enhancement and segmentation algorithms will be applied to extract information intelligently.

ACKNOWLEDGEMENT

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