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NONDESTRUCTIVE INSPECTION (NDI) THROUGH HIGH-VELOCITY OXYGEN FUEL (HVOF) THERMAL SPRAY COATINGS

Delivery Order 0001: Nondestructive Evaluation Exploratory Development for Air Force Systems

Noel Tracy

Universal Technology Corp.
1270 N. Fairfield Road
Dayton, OH 45432-2600

1st Lt Sandra Davis and John Brausch

Materials Integrity Branch (AFRL/MLSA)
Systems Support Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7750

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/s/

JOHN BRAUSCH
Team Leader
Structural Matls & NDE Eval Team
Materials Integrity Branch

/s/

LARRY PERKINS
Acting Chief
Materials Integrity Branch
Materials & Manufacturing Directorate

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Noel Tracy (Universal Technology Corp.)
1st Lt Sandra Davis and John Brausch (AFRL/MLSA)

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Universal Technology Corp.
1270 N. Fairfield Road
Dayton, OH 45432-2600

Materials Integrity Branch (AFRL/MLSA)
Systems Support Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7750

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14. ABSTRACT

High Velocity Oxygen Fuel (HVOF) thermal spray coatings are the leading candidates to replace electrolytic hard chrome (EHC) coatings on critical high strength steel components such as aircraft landing gear. HVOF qualification as an acceptable replacement for hard chrome plating has not been fully demonstrated, particularly for fatigue-sensitive aircraft components. One area lacking is the ability to inspect through these coatings for substrate damage. Three nondestructive inspection (NDI) techniques were used to determine the detectability of fatigue cracks under the HVOF coatings. The detectability of cracks through HVOF using magnetic particle inspection proved to be unsuccessful. Crack detection through HVOF coatings using eddy current proved to be unreliable and ambiguous. Ultrasonic inspection through HVOF coatings proved to be a reliable method of crack detection for this study's test specimen geometry.

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Executive Summary

High Velocity Oxygen Fuel (HVOF) thermal spray coatings are the leading candidates to replace electrolytic hard chrome (EHC) coatings on critical high strength steel components such as aircraft landing gear. HVOF qualification as an acceptable replacement for hard chrome plating has not been fully demonstrated, particularly for fatigue-sensitive aircraft components. One area lacking is the ability to inspect through these coatings for substrate damage. Three nondestructive inspection (NDI) techniques were used to determine the detectability of fatigue cracks under the HVOF coatings. The detectability of cracks through HVOF using magnetic particle inspection proved to be unsuccessful. Crack detection through HVOF coatings using eddy current proved to be unreliable and ambiguous. Ultrasonic inspection through HVOF coatings proved to be a reliable method of crack detection for this study's test specimen geometry.

Background

High Velocity Oxygen Fuel (HVOF) thermal spray coatings are the leading candidates to replace electrolytic hard chrome (EHC) coatings on critical high strength steel components such as aircraft landing gear. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state; Hexavalent chromium (hex-Cr) is a known carcinogen having a level of toxicity greater than arsenic or cadmium. As a result, wastes generated from plating operations must be disposed of as hazardous waste and plating operations must abide by the Environmental Protection Agency (EPA) emissions standards and the Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL). The cost of compliance for any business could be upwards of $45 million[1] per year in collection, treatment, and disposal costs, plus a one time facilities cost of $22 million[1] to upgrade exhaust and ventilation equipment, personal protective gear, and industrial waste facilities. In addition to the high cost, turnaround times for the processing of aircraft components would be significantly increased, impacting mission readiness.

There are a wide number of applications for HVOF coatings; however, their qualification as an acceptable replacement for hard chrome plating has not been fully demonstrated, particularly for fatigue-sensitive aircraft components. One area lacking analysis is the ability to inspect through these coatings for substrate damage. Landing gear are routinely inspected by visual and nondestructive inspection (NDI) techniques to determine if substrate cracks are present. The ability and limitations for detection of substrate cracks under chrome plating is well established. The ability to detect substrate cracks under HVOF coatings has yet to be demonstrated. The goal of this effort was to compare the detectability of fatigue cracks under chrome and HVOF coatings using three classic NDI methods: ultrasonics, eddy current, and magnetic particle.

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[1] Joint Test Protocol Validation of WC/Co and WC/CoCr HVOF Thermal Spray Coatings as a Replacement of Hard Chrome Plating on Aircraft Landing Gear, U.S. Hard Chrome Alternatives Team (HCAT) and Canada Hard Chrome Alternatives Team (CHCAT)

Objective

The objective of this evaluation was to assess the detectability of fatigue flaws in 4340 steel which has been coated with WC-Co (83%/17%) using the High-Velocity Oxygen-Fuel (HVOF) thermal spraying method and compare the results to chrome-plated specimens. Traditional nondestructive evaluation (NDE) methods, ultrasonics, magnetic particle and eddy-current, were the methods of interest.

Approach

Thirty-eight flat plates of 4340 steel, each with 2 fatigue cracks were obtained (see Figure 1a). A baseline characterization of the cracks, on the uncoated specimens, was performed with magnetic particle, eddy current and ultrasonic inspections. The specimens were separated into 5 different groups with approximately equal flaw size distributions. Four groups were plated with the received 0.003 or 0.010 mils of Electrolytic Hard Chrome (EHC) or WC-Co High Velocity Oxygen Fuel (HVOF) thermal spray coating and one group remained uncoated. After the coatings were applied, the specimens were once again characterized with the three NDI methods. Finally, the data was analyzed and processed to establish crack detection limits.

Specimen Description and Processing

The thirty-eight specimens used for this experiment were manufactured from a single lot of 4340 steel. Each specimen-blank size was approximately 0.3 inches thick, 2 inches wide and 14 inches long. The specimen blanks were fabricated by rough machining, followed by vacuum heat treat to 260-280 ksi tensile strength. A low stress grinding was then accomplished to bring the specimens to final dimension. Nital etching in accordance with MIL-STD-867 was conducted on all specimens to examine for grind burns. All specimens were baked after nital etching to remove residual hydrogen. The width and length for the final flat plate geometry remained the same as the blank size. The respective thicknesses of the plates after coating are listed in Table 1. The original estimated lengths and depths for all flaws can be found in Table 2.

Preparation of the specimens for crack growth began by inserting pre-flaws into test specimens by Electrostatic Discharge Machining. The approximate dimensions of the preflaws were 0.02 to 0.080-inch (depth) by 0.04 to 0.160-inch (length).

Test specimens were loaded in 3-point bending and cycled under tension-tension conditions to produce fatigue cracks (see Figure 1b). Crack growth rate was determined and the growth of the fatigue cracks was visually monitored to ensure that the fatigue cracks did not exceed the desired lengths. The sizes of the resulting fatigue cracks ranged from 0.040 to 0.250 inch in length and 0.020 to 0.080 inch in depth. Verification of actual depths was accomplished by breaking open, via overload, several specimens containing the range of crack lengths and visually inspecting their fracture surfaces. After the fatigue cracks were grown, the specimens were machined to remove starting flaws and achieve the desired surface flaw size. Additionally, extra load cycles were applied to specimens to "open up" the cracks which were generally smeared over as a result of machining. This allowed visual verification of the final fatigue crack before shot peening and HVOF coating application.

Shot peening was performed under computer control and in accordance with AMS 2432. It was conducted over the entire surface of all the specimens with a 100% surface coverage. Specimens coated with WC-Co HVOF coating were grit blasted after they were shot peened. Grit blasting was accomplished with 54-grit aluminum oxide at 60 psi at a 90-degree angle of impingement. The grit blast was performed in accordance with MIL-STD-1504.

The specimens were then divided into five groups (A, B, C, D, and E) with approximately equal flaw size distributions.

Electrolytic hard chrome (EHC) was deposited on Group A (8 specimens) and Group B (7 specimens) in accordance with MIL-STD-1501. The thicknesses applied were 0.003-inch (Group A) and 0.010-inch (Group B) +/- 0.0005-inch. Special care was taken when coating to ensure uniform thickness (i.e., the panel was centered between electrodes).

The 83/17 WC-Co deposited by the HVOF technique was deposited on Groups C (8 specimens) and D (7 specimens). The deposition was conducted in accordance with Boeing Specification BAC 5851, Class 2, Type I with the following clarifications:

a) The coatings were deposited using a Tafa-JP5000 gun.
b) The equipment manufacturer recommended the WC-Co powder material.
c) Uniform deposition conditions were utilized for all specimens.
d) Air-cooling was utilized to ensure the specimen surface did not exceed 300F.
e) The WC-Co was deposited directly onto the substrate material with no interfacial layer.
f) No sealer was applied to the HVOF coatings.
g) The coating thicknesses after grinding were 0.003-inch (Group C) and 0.010-inch (Group D) inches +/- 0.0005-inch.
h) All HVOF coatings were deposited to an Almen number of 8-12N.

Group E (8 specimens) remained uncoated. These specimens were used to provide a consistent baseline for detectability comparison.

Inspection Procedure Description

Magnetic Particle Inspection

The procedure for magnetic particle inspection of the uncoated specimens began with cleaning the part with isopropyl alcohol and a rag. A specimen was placed in the inspection area with one end raised approximately four inches. A Parker Probe was used as the magnetizing unit. The Parker Probe legs were placed

flat against the specimen approximately one inch from each end. The Parker Probe was set on AC and the highest level of magnetizing power. The probe was used to magnetize the specimen for approximately 6 seconds. Magnetic particle suspension was then immediately poured over the specimen. The specimen was then immediately magnetized for an additional 8 seconds (see Figures 2a and 2b). Next, the specimen was propped up nearly vertical allowing the magnetic particle suspension to continue to flow perpendicular to the cracks. This facilitated an optimum accumulation of fluorescent particles at crack sites. A specimen was allowed to drain for approximately 30 seconds. Then the specimen was inspected under an ultraviolet light (UV-A) (see Figure 3). After identifying the cracks, digital pictures of the fluorescent indications were obtained. The pictures were downloaded into an image processing software enabling the measurement of the indication lengths (see Figure 3).

Ultrasonic Inspection

Before the specimens were coated, a manual ultrasonic pulse-echo, shear-wave technique was developed with a Krautkramer Model 15S ultrasonic instrument and a Krautkramer KB-A (part number 90289) ¼ inch, 10 MHz transducer. The transducer was attached to a plastic wedge in order to produce a shear-wave ultrasonic beam in a specimen at a 60-degree angle (with respect to a line perpendicular to the surface of the specimen). The transducer was placed on the same surface as a crack so that the sound beam bounced off the opposite surface back towards the crack. The transducer was scanned and rotated by hand until the amplitude of the reflected signal from the crack was maximized. Figure 4a depicts the ultrasonic equipment and setup. Figure 4b shows a close-up of the ultrasonic probe. Figure 4c is a picture of an ultrasonic response.

Eddy Current Inspection

A manual eddy current technique was developed with a Nortec $19e^{II}$ instrument and a Nortec absolute probe (part number 972511) with a frequency range of 100 to 500 kHz. The instrument was set to operate at 200 kHz. The probe was inserted into a holder to maintain its orientation perpendicular to the inspection surface. The probe was scanned by hand until a crack signal was maximized. Figure 5a depicts the eddy current inspection setup. In order to reduce the effects of variable permeability on the eddy current signals, each specimen was first magnetized with the Parker Probe set to apply direct-current magnetization.

After the coatings were applied, a custom eddy current probe became available. This NDT Engineering Corporation 500kHz probe (part number NEC-2008), was specially made for inspecting steel and contained two magnets embedded into the probe case. The magnets provided a saturated field in the specimen and had the same effect as the magnetization with the yoke before inspection with the absolute probe. Figure 5a depicts the eddy current inspection setup with the special probe. Figure 5b shows the two types of probes. The probes were interchangeable and required simple readjustment of instrument parameters for optimum operation. As before, the probe was scanned until the maximum indication was obtained from each crack. The vertical amplitude of each indication was then recorded.

Baseline Characterization

All 38 cracked specimens were nondestructively characterized before coating application. Magnetic particle, eddy current, and ultrasonic inspections were conducted to provide a baseline of substrate cracks for each method.

It was discovered that the initial magnetic particle inspection was unable to detect cracks in the uncoated shot-peened specimens. This was a result of the shot-peen restricting the surface magnetic domains preventing them from aligning with the applied magnetic field. Flux leakage was therefore prevented from forming at the crack sites resulting in no particles collecting to form indications. This situation was rectified by grinding 0.003-inch of material from each plate's surface.

After the 0.003-inch of material were removed, magnetic particle testing detected cracks on all specimens except for two; specimen 17 had no crack indications and only one crack on specimen 44 (crack 44b) was detected. The undetected flaws (approximately 0.036″ in length and 0.017″ in depth) were considered too small to detect with this method. The baseline magnetic particle measurements are plotted in Figure 7.

The eddy current procedure, outlined in the previous section, was able to detect cracks on all the uncoated specimens. However, the signal-to-noise ratio was not sufficient for reliable detection of cracks less than 0.150-inch long. The data is plotted in Figure 8.

Ultrasonic testing detected all cracks on the uncoated specimens with the exception of three: 44b, 48a, and 48b. The data is plotted in Figure 9.

Post Coating Inspection Results

Magnetic Particle Results

After the specimens were coated with EHC and HVOF the magnetic particle inspection was reaccomplished. Because of the additional surface coatings additional technique development was required to establish the most effective magnetization procedure with the coatings applied. Several techniques, including bench top AC and DC fields, half-wave rectification, as well as low to very high magnetization currents were attempted. After exhausting all magnetic particle inspection options it was found that magnetic particle was ineffective on all the coated specimens.

Ultrasonic Results

The ultrasonic inspection was again performed after the specimens were coated. The coated results are presented in Figure 9 as the red data. The inspection of the uncoated specimens (Group E) was repeated at the same time inspections of the coated specimens were conducted.

Except for the two cracks with lengths around 0.230-inch, the data in Figure 9 illustrates the relationship between crack surface area and ultrasonic response. The noted exceptions are cracks in specimen #8, which was coated with 0.003-inch of chrome. The reason for the drastic drop-off in ultrasonic response remains unknown. Within the range of anticipated data scatter, application of the coatings had no effect on the ultrasonic responses from the cracks.

Eddy Current Results

Eddy current inspection of the coated specimens was again performed. The results are presented in Figures 10 through 13. As expected the coating significantly reduced the sensitivity of the eddy current inspection. The signal-to-noise for many of the eddy current indications were very poor and often of the same signal strength as the surrounding baseline noise.

Figure 14 provides examples of an eddy current signal response from several cracks. Figure 14a is for a 0.075-inch long crack, the same one for which the ultrasonic signal is shown in Figure 4c. Figure 14b shows the eddy current signal from a 0.228-inch crack in a specimen with 0.010-inch HVOF coating. The signal

from a 0.233-inch crack in a specimen with 0.003-inch of HVOF coating was similar to Figure 14b, except one division higher. Figure 14c shows, the eddy current signal from a 0.248-inch crack in a specimen with 0.003-inch of chrome coating. Figure 14d shows what happens to Figure 14c with additional scanning of the probe over the specimen surface (simulating an actual inspection). The accumulated noise signals from the variable magnetic permeability in the specimen obscures the low amplitude signal from the crack. Additional scanning on the specimens coated with HVOF produces similar results. Furthermore, the signal amplitudes are directly proportional to the speed at which the probe is scanned over a crack. Although the two different types of eddy current probes were used for the uncoated Group E specimens, Figure 8 shows the data did not differ significantly for the two independent eddy current inspections.

Discussion

The data presented clearly indicates that the addition of HVOF and Chrome surface coatings significantly reduce the detectability of fatigue cracks using magnetic particle inspection. Generally, magnetic particle inspection is not recommended if coatings exceed 0.002-inch, especially if the coating, such as chrome, is non-ferromagnetic. The HVOF coating is ferromagnetic, but its magnetic characteristics were not available. However, from the data, it is obvious that the HVOF coatings significantly degraded the capability of the magnetic particle inspection.

One advantage of magnetic particle inspection is the methods sensitivity to defects just below the surface. However, in this case the subsurface defects remained undetectable. It is unknown what effect the lack of a surface crack in the coating had on the detectability of the substrate fatigue cracking. The existence of a substrate crack without a coating crack is not expected to occur in nature. This effect should be studied further to more completely understand the poor performance of the magnetic particle inspection.

Initially, the inability to obtain magnetic particle indications of cracks in the uncoated specimens was due to the specimens shot peened condition. The intent of shot-peening is to induce compressive stresses to inhibit crack growth. However, high compressive stresses adversely affect the movement of magnetic domains. The result is insufficient magnetization for proper magnetic particle inspection. Removing 0.003-inch of material from the specimens reduced the depth of the shot-peen effects and improved the results of the magnetic particle inspection.

Eddy current inspection of ferromagnetic materials is inherently difficult because slight variations in magnetic permeability will affect the eddy current responses. Attempts to overcome these effects by magnetizing the specimens and using special probes with magnets to align the local magnetic domains are not always completely successful. Adding coating further reduced the sensitivity of the eddy current inspection. A ferromagnetic coating (HVOF) with its own permeability characteristics added another variable that degrades the inspection.

The ultrasonic response from the coated specimens did not, in almost all cases, differ from the response from the uncoated specimens. Figure 4c is a typical ultrasonic instrument display showing a signal indicting the sound reflected from a 0.075-inch long crack. The signal-to-noise ratio is very large for this crack and for all larger cracks. Noise signals generally arise from the acoustic properties of a material. As the instrument amplification is raised to detect smaller cracks, the noise also increases. For the specimens in this study, the signal-to-noise ratio for a 0.050-inch long crack was 2:1, an acceptable level but one that reduces the reliability of manual ultrasonic inspection.

Only the ultrasonic technique could reliably detect the cracks in specimens coated with HVOF or chrome. On real aircraft parts, the ability to use the technique would greatly depend on the part geometry.

Conclusions

The ultrasonic technique utilized and demonstrated very good detectability of fatigue cracks through both HVOF and chrome coatings.

The eddy current technique produces ambiguous results, even on uncoated specimens. More study is needed to reduce the ambiguity by characterizing the signals, especially the phase, in order to determine if it is possible to discriminate between crack signals and magnetic-noise signals. On coated specimens used in this study eddy current detection of cracks with lengths less than 0.250-inch is not predictable.

Magnetic particle inspection was found to be completely ineffective through both the HVOF and chrome coatings for the detection of fatigue cracks. Further assessment of the effects of the uncracked surface coatings on substrate crack detection is required.

FIGURES

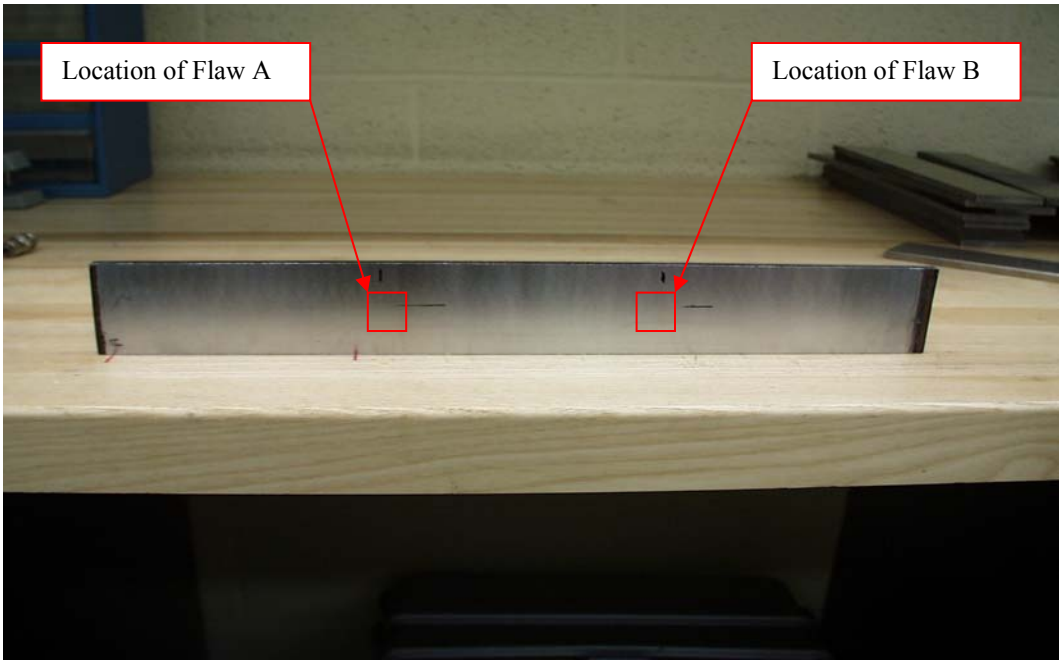


Figure 1a. A picture of a 4340 steel specimen.

Table 1.
Thickness of Specimens Before and After Coatings

Plate Number	Plate Uncoated Thickness (inch)	Final Ground Thickness (inch)
HVOF 0.003 inch thick coating		
11	0.258	0.261
33	0.259	0.262
38	0.259	0.262
36	0.259	0.262
41	0.026	0.263
35	0.26	0.263
1	0.0259	0.262
15	0.261	0.264
HVOF 0.010 inch thick coating		
47	0.259	0.269
4	0.259	0.269
27	0.26	0.27
18	0.253	0.263
9	0.259	0.269
49	0.26	0.27
37	0.259	0.0269
Cr 0.003 thick inch coating		
8	0.259	0.262
2	0.26	0.263
40	0.259	0.262
7	0.259	0.262
22	0.26	0.263
25	0.26	0.263
20	0.259	0.262
44	0.26	0.263
Cr 0.010 inch thick coating		
21	0.259	0.269
13	0.26	0.27
24	0.257	0.267
28	0.259	0.269
34	0.26	0.27
6	0.259	0.269
48	0.26	0.27

Table 2.

NDI Surface Flaw Specimen Dimensions				
Specimen I.D. Number	Flaw A approx. length (in)	Flaw A approx. depth (in)	Flaw B approx length (in)	Flaw B approx. depth (in)
1	0.045	0.0134	0.0418	0.012
2	0.2143	0.0766	0.2181	0.0777
3	0.2245	0.0795	0.2207	0.0784
4	0.2007	0.0726	0.2057	0.0741
6	0.0825	0.0295	0.0873	0.0315
7	0.152	0.0566	0.148	0.0552
8	0.234	0.082	0.2292	0.0808
9	0.1091	0.0404	0.1063	0.0393
11	0.2324	0.0816	0.2227	0.079
12	0.1584	0.0588	0.1655	0.0613
13	0.2078	0.0747	0.2102	0.0754
15	0.1409	0.0526	0.1245	0.0464
17	0.0543	0.0174	0.0457	0.0136
18	0.1435	0.051	0.142	0.0504
20	0.0605	0.02	0.0497	0.0154
21	0.2252	0.0797	0.2401	0.0836
22	0.1016	0.0374	0.1149	0.0427
23	0.0473	0.0144	0.0417	0.0119
24	0.1808	0.0663	0.183	0.0671
25	0.0964	0.0353	0.0854	0.0307
27	0.1722	0.0635	0.1795	0.0659
28	0.1788	0.0657	0.1521	0.0566
29	0.1766	0.065	0.1009	0.0371
33	0.1968	0.0714	0.1902	0.0693
34	0.1164	0.0433	0.1189	0.0443
35	0.0514	0.0161	0.0409	0.0116
36	0.0999	0.036	0.0904	0.0328
37	0.0603	0.02	0.0687	0.0236
38	0.1755	0.0646	0.16	0.0594
39	0.0752	0.0264	0.0855	0.0308
40	0.2475	0.0855	0.1247	0.0465
41	0.0657	0.0223	0.0755	0.0265
44	0.0359	0.0095	0.037	0.0099
46	0.2236	0.0792	0.2506	0.0863
47	0.2375	0.0829	0.2284	0.0805
48	0.0531	0.0168	0.0466	0.014
49	0.072	0.025	0.0798	0.0283
50	0.1875	0.0679	0.194	0.0705

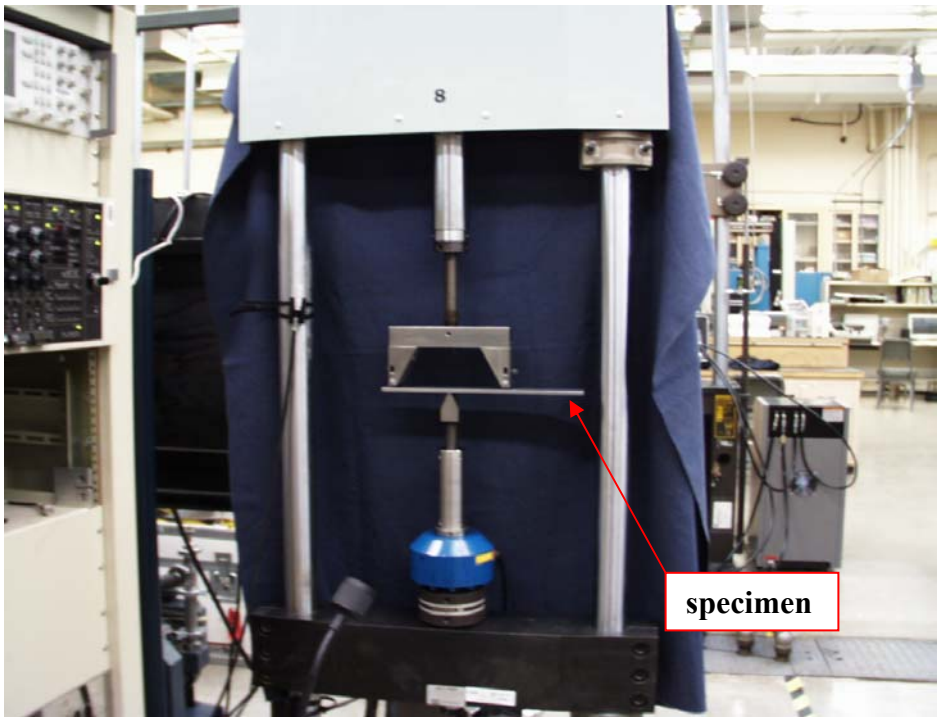


Figure 1b. Three-point bending fixture with which each specimen was cycled under tension conditions to produce a fatigue crack.

Figure 2a. Magnetic particle inspection using Parker Probe.

Figure 2b. Magnetic particle bath being poured onto specimen.

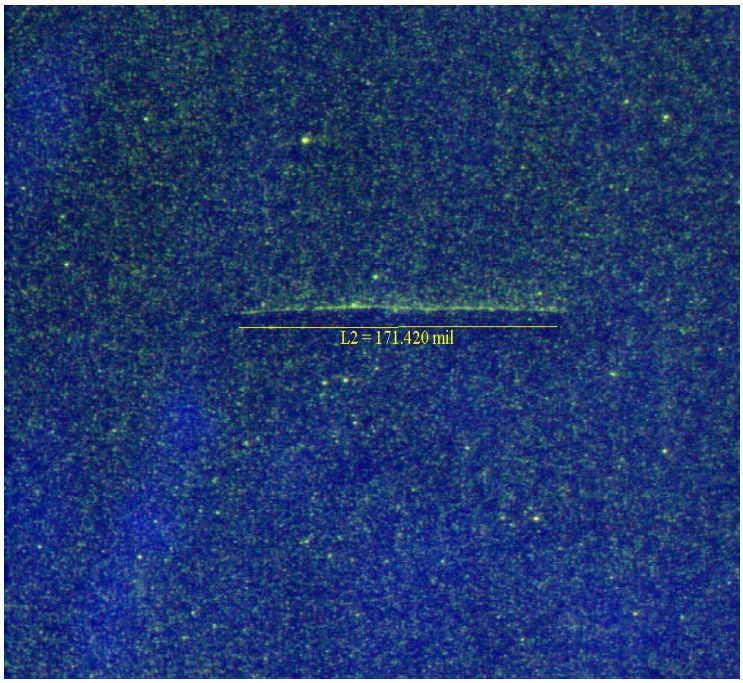


Figure 3. Magnetic particle inspection crack indication on an uncoated specimen. The scale annotation illustrates crack indication measurement using image analysis.

Figure 4a. Ultrasonic inspection setup.

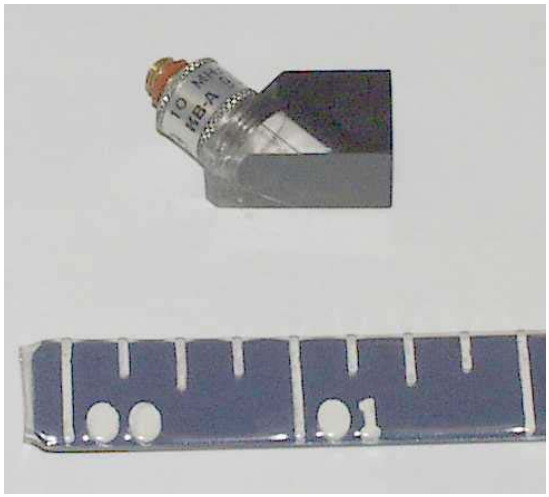


Figure 4b. Ultrasonic probe.

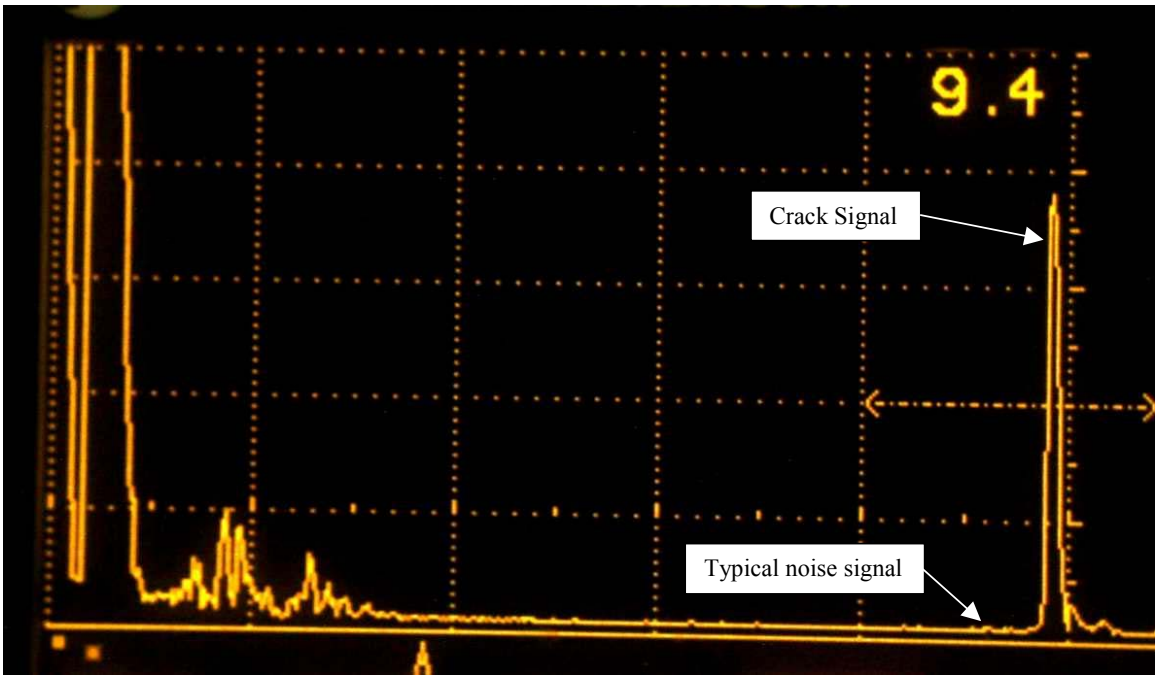


Figure 4c. Ultrasonic instrument display showing the reflected signal from a 0.075-inch long crack.

Figure 5a. Eddy current inspection setup.

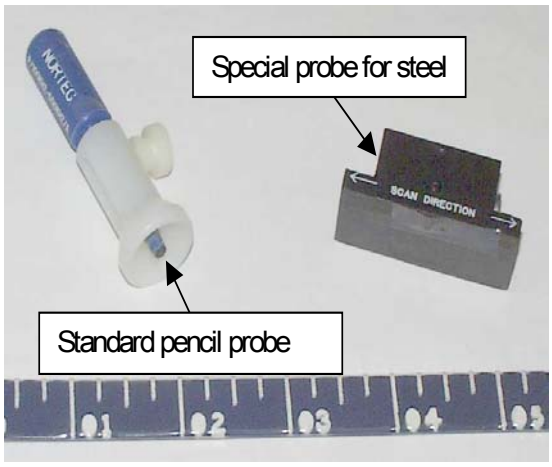


Figure 5b. Eddy current probes

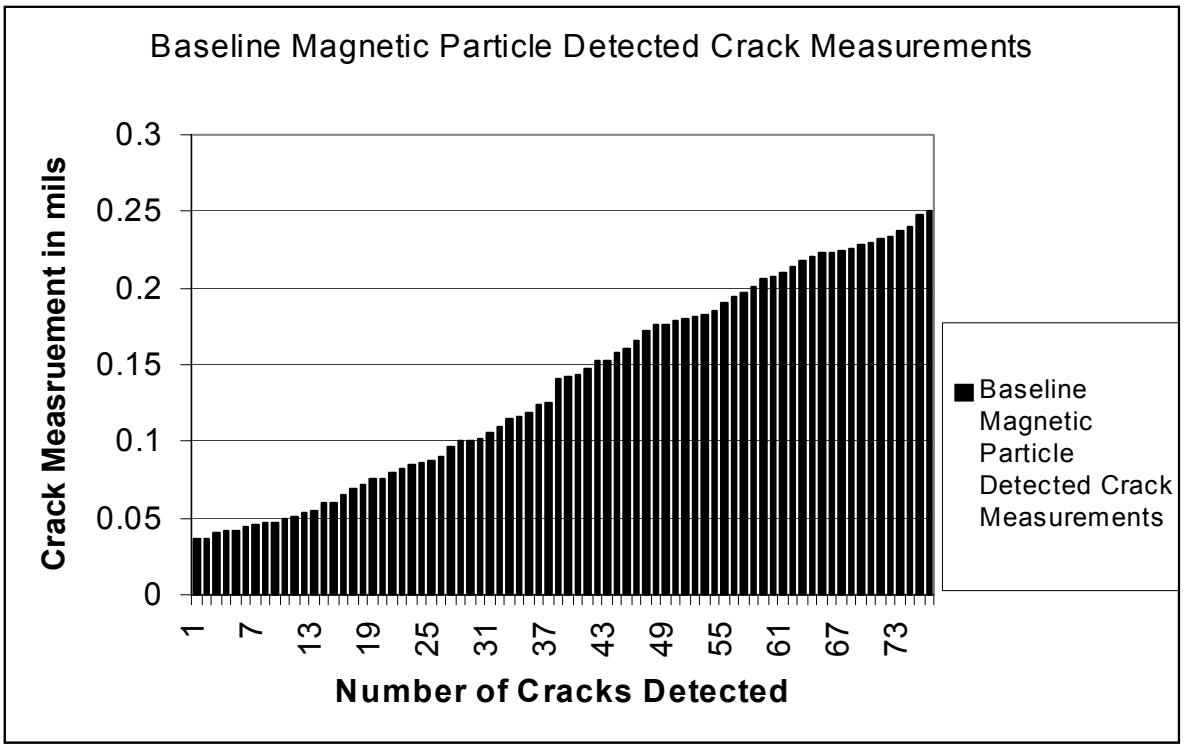


Figure 7. Baseline magnetic particle crack measurements.

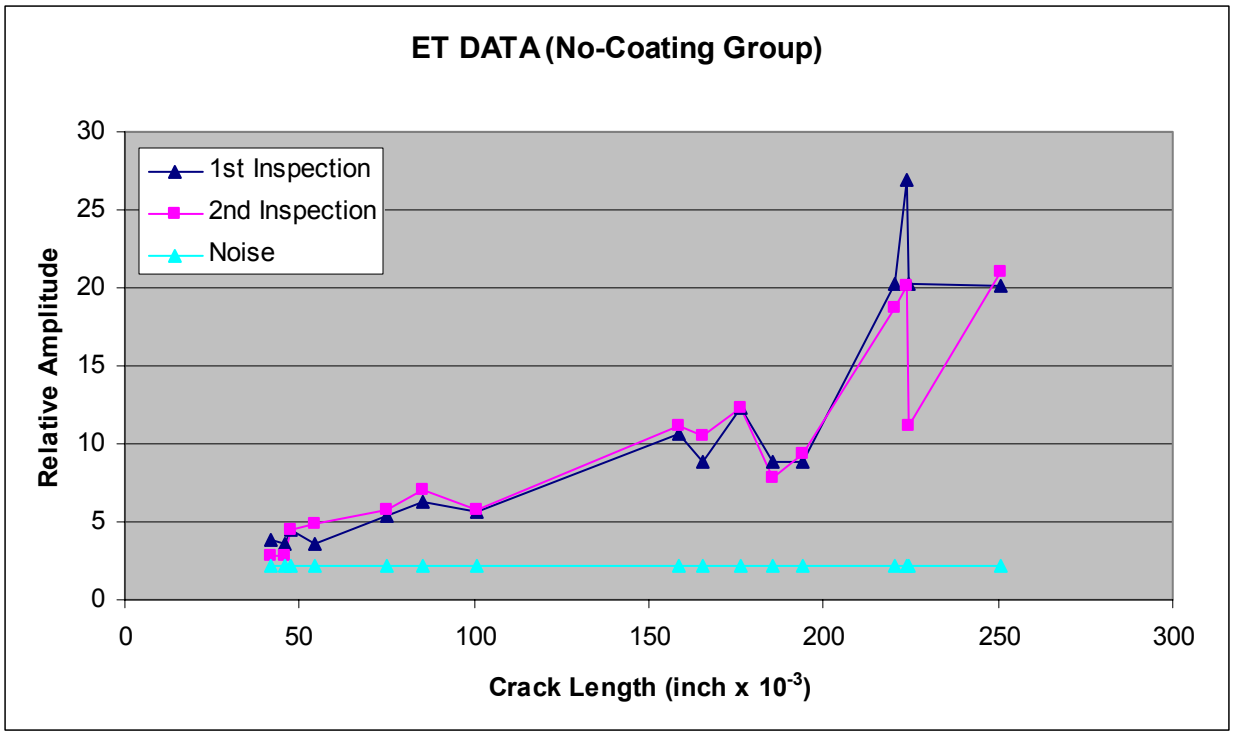


Figure 8. Eddy current data for specimens that were not coated.

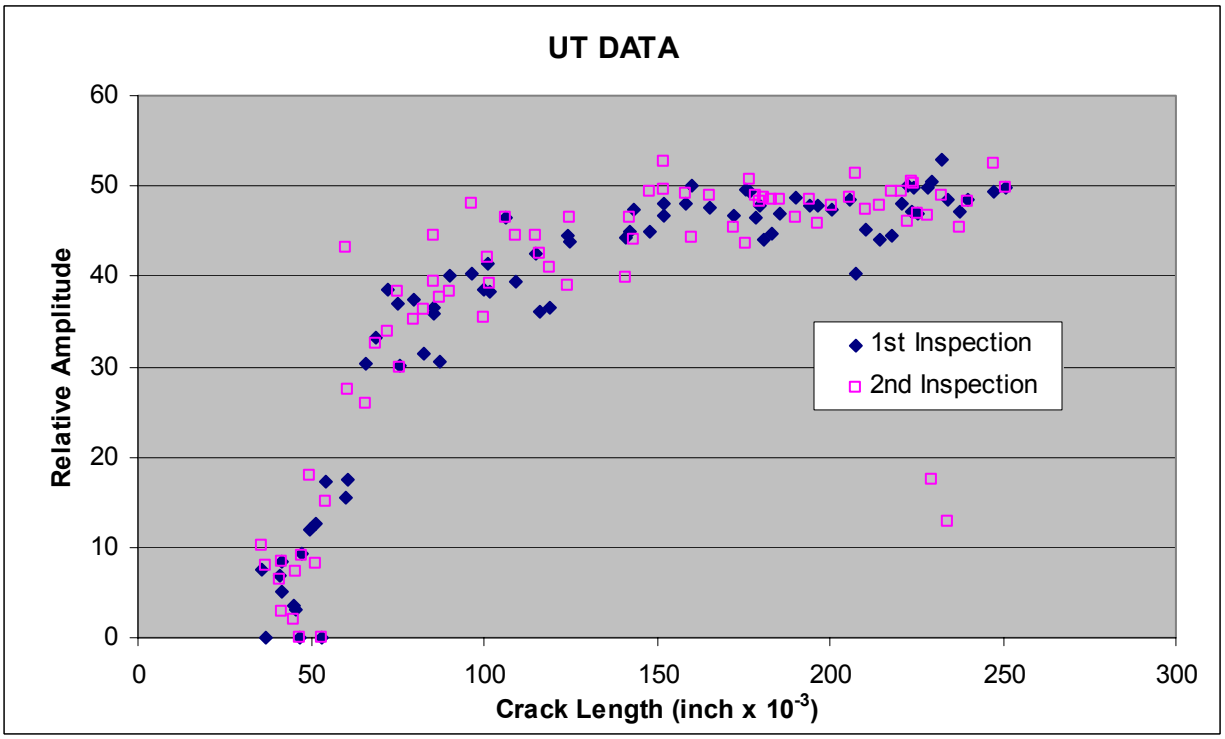


Figure 9. Ultrasonic data for all specimens.

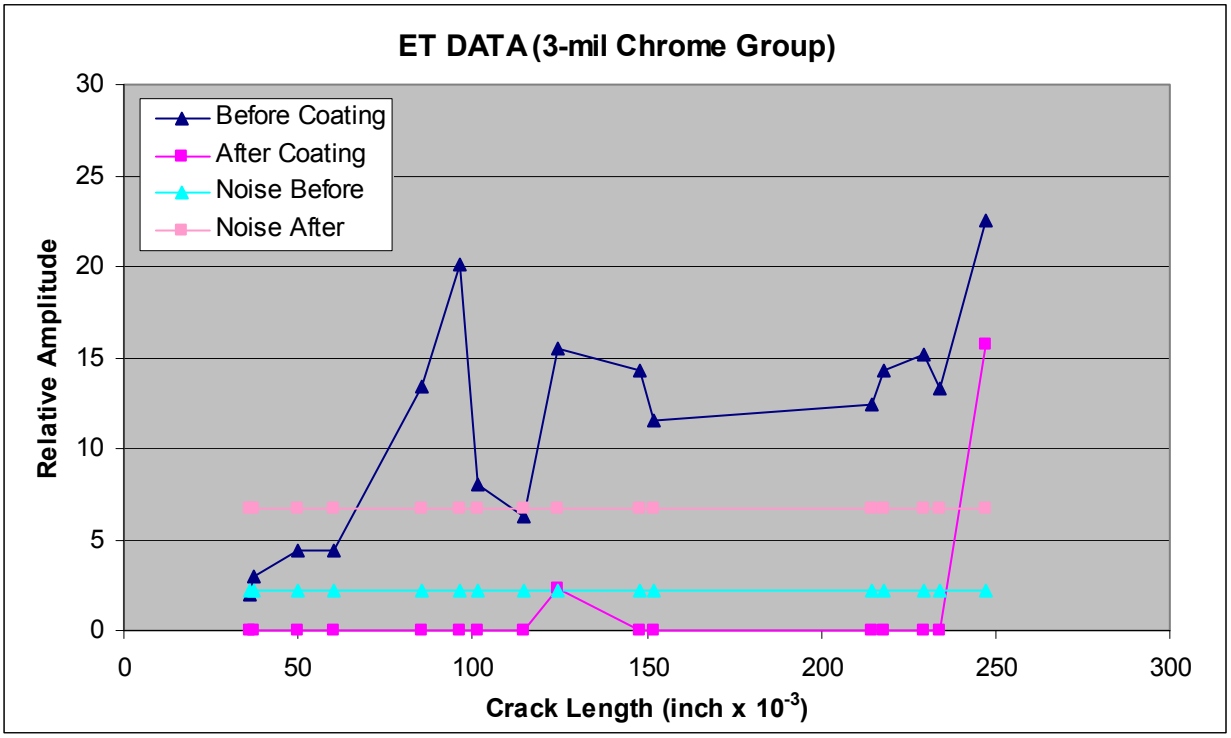


Figure 10. Eddy current data for specimens on which 0.003 inch of chrome coating was applied.

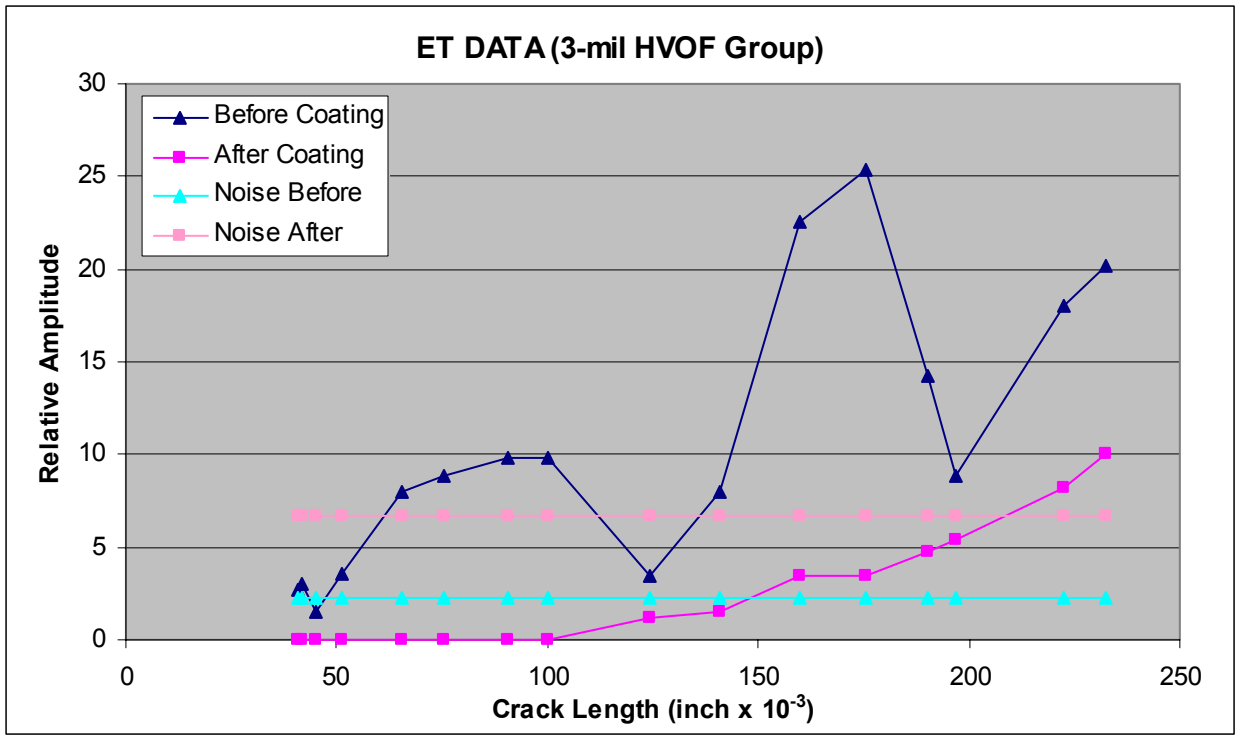


Figure 11. Eddy Current data for specimens on which 0.003 inch of HVOF coating was applied.

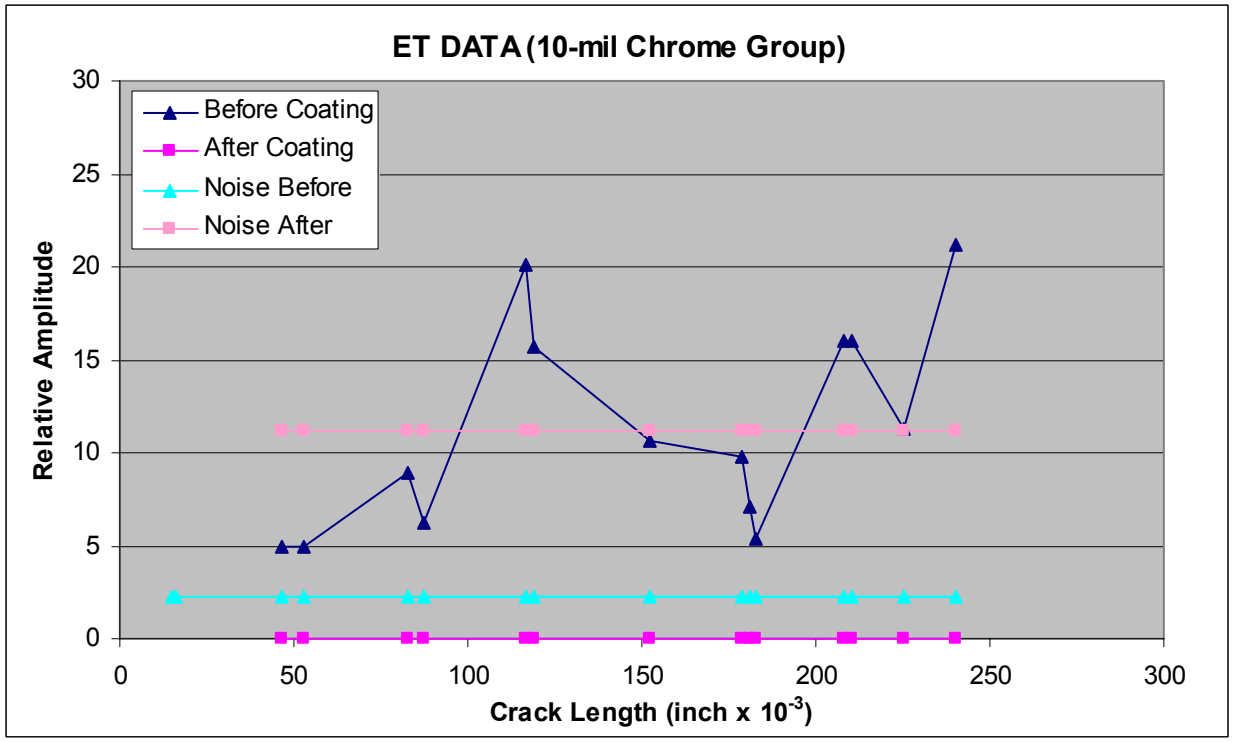


Figure 12. Eddy current data for specimens on which 0.010 inch of chrome was applied.

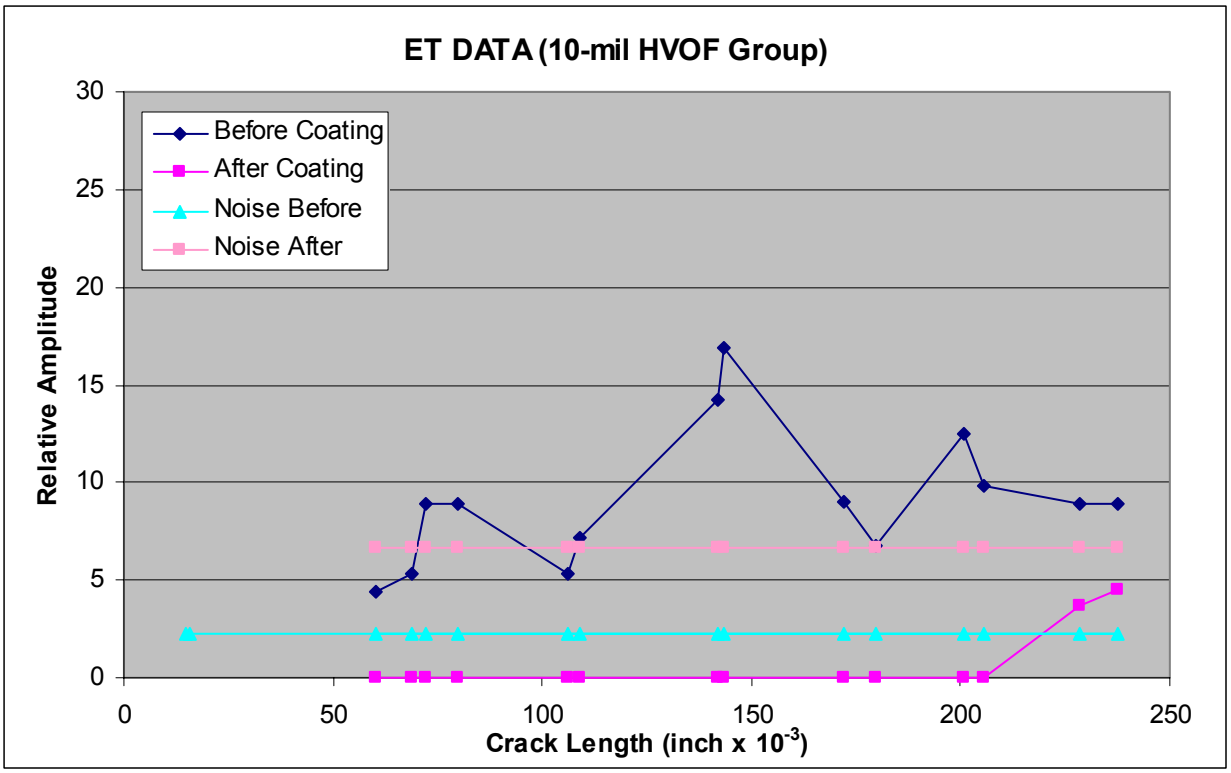
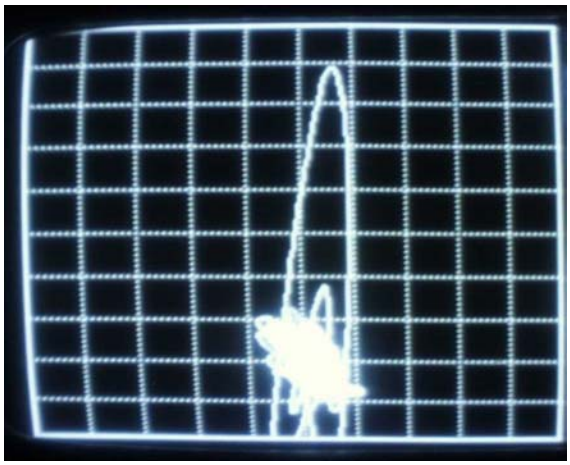
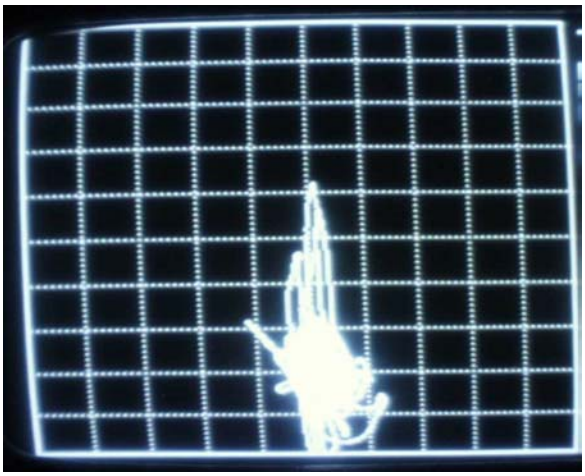


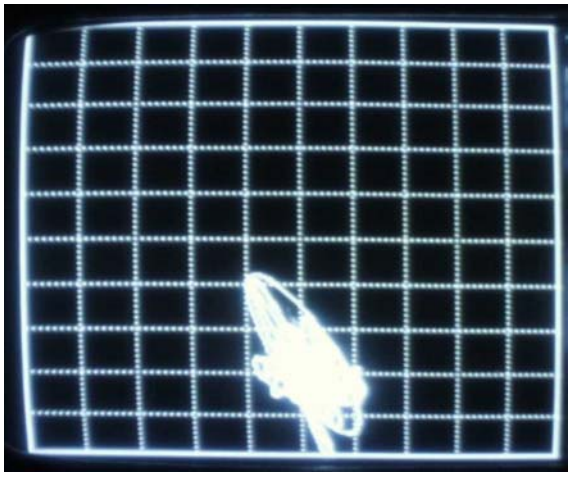
Figure 13. Eddy current data for specimens on which 0.010 inch of HVOF coating was applied.



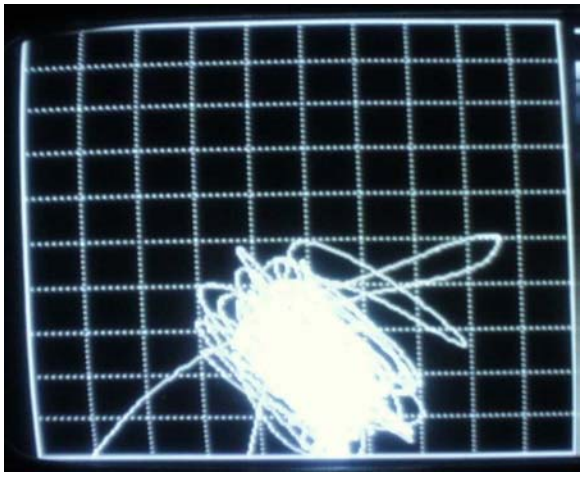
(a) Indication from a 0.075-inch uncoated specimen.



(b) Indication from a 0.223-inch crack in Specimen with 0.010-inch HVOF coating.



(c) Indication from a 0.248-inch crack in specimen with 0.003-inch Cr coating.



(d) Indications of noise accumulated during Probe scanning, obscuring crack signal shown in (c).

Figure 14. Eddy Current Indications.