Engineered Applications of ElectroSpark Deposition (ESD) For Component Repair

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Advanced Surfaces and Processes, Inc will identify, evaluate and qualify applications of the Electrospark Deposition (ESD) process for repair of gas turbine engine (GTE) components. This effort is in support of the Propulsion Environmental Working Group's (PEWG) objective of finding and implementing cost effective industrial materials and processes to reduce DoD environmental compliance burdens and employee health and safety risks associated with the manufacturing, operation, and maintenance of GTEs.

Six alloys, 17-4 PH, 410 SS, Hastelloy X, Haynes 188, Inconel 625 and Inconel 718, were selected and repaired with the ESD process. Material testing included microscopy, evaluation for discontinuities, cracking, bond quality, grain structure, HAZ and microhardness. Mechanical testing included low cycle fatigue, tensile and bend testing. Based on the results, two GTE components have been identified for further development.

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Introduction

The Electro-Spark Deposition (ESD) process is a capacitor discharge, micro-arc welding process that utilizes short duration electrical pulses, discharged at controlled energy levels, to create a metallurgically bonded surface modification or build-up. Typical tribological uses for ESD include: the deposition of engineered electrode materials for surface wear improvement, creation of a corrosion barrier, or changing the coefficient of friction characteristics of a given material surface. ESD is also an important tool for use in the repair of defects in a wide variety of metallic substrate materials not readily welded by other more conventional weld repair methods such as MIG or TIG, or where a heat affected zone (HAZ) is a consideration.

Current Efforts

Current efforts in ESD development include multiple on-going projects in the tri-services. The most significant are Air Force (project conducted by Advanced Surfaces), Navy (projects conducted by Carderock and North Island), and Army (project conducted by Anniston Army Depot). This paper addresses the achievements and direction of the Air Force efforts. However, a short summary of the status of the Navy and Army efforts is included.

<u>*ESD for Naval components (Carderock)*</u>

Carderock has developed a successful repair for K-Monel for the Steering and Diving Control Rod. They are currently exploring other applications.

<u>*ESD for Naval components (North Island)*</u>

North Island Naval Air Depot has successful repairs for HP 9-4-30 and AerMet 100 for launch bar lugs on the F 18 and hard chrome plate for actuators, (developed by ASAP in coordination with NI). They are currently exploring other applications.

<u>*ESD for Army components (Anniston)*</u>

Anniston Army Depot has developed a successful repair for the 4130 steel Abrams M1A1 tank Cradle. This repair is in production. They are currently exploring other applications, including an Inconel 718 spline coupling for turbine transmission.

<u>*ESD for Air Force components (ASAP)*</u>

Advanced Surfaces has been contracted to direct a PEWG/ESTCP project, *Engineered Applications of Electro-Spark Deposition (ESD) for GTE Repair*. The objective of this project is to identify, evaluate and qualify applications of the Electrospark Deposition (ESD) process for repair of gas turbine engine components. Phases I and II were completed as of June 30, 2003, with the evaluation of seven alloys: Inconel 625, Inconel 718, Hastelloy X, Haynes 188, 410 stainless steel, 17-4 PH and Ti-6Al-4V. Edison Welding Institute (EWI) conducted mechanical testing on specimens of Inconel 718. Portland State University (PSU) conducted materials testing on all seven materials, and mechanical testing on Inconel 718 and 17-4 PH. An interim report, summarizing the efforts through Phase II is available on the HCAT website: *www.HCAT.org*. Two components were selected for development in Phase III. They are the #5 bearing housing (Pratt & Whitney), which requires dimensional restoration and the TF39 shaft (GEAE), which requires chrome plate repair. Development of repair on these components is in progress.

September, 2003, launched an extension of this project with ESTCP/HCAT/PEWG for further development of the ESD process. Additional substrate materials were added, as well as repair of non-ESD coatings and incorporation of supplementary mechanical testing. The objective of this extension is to prepare a Demonstration Plan, which will include a Joint Test Protocol (JTP), and initiate studies to optimize the ESD process. The JTP will be executed in two parts; optimizing the ESD process and evaluating the material properties of ESD. A draft of the JTP is available on the HCAT website. Multiple OEMs and depots are involved in the development and execution of this Demonstration Plan, including Advanced Surfaces and Processes, Inc. (ASAP), Air Force Research Lab (AFRL) , EWI, Engelhard Surface Technologies, GEAE, Metcut Research, Inc, Oklahoma City Air Logistics Center (OC-ALC), PSU, Pratt and Whitney, Rowan Technology Group and Sauer Engineering. The demonstration plan will be executed with actual GTE components. One component has been selected, the 10-12 Stator Segment (Pratt & Whitney).

This paper will address the results of the initial studies conducted under the PEWG/ESTCP project. When this paper was written, the JTP has not been developed. Therefore, the test protocols were as follows:

- Advanced Surfaces performed materials testing on a subset of the coupons, as well as managed the project and coordinated the efforts with the subcontractors.
- Portland State University performed material testing on all coupons. They also performed mechanical testing on Inconel 718 and 17-4 PH (not discussed in this paper).
- Edison Welding Institute performed mechanical testing on Inconel 718.

A *Design of Experiment* (DOE) was formulated by maintaining all parameters constant and varying the equipment parameters of capacitance, voltage, current and pulse rate. This resulted in 36 coupons for each of the six materials, for a total matrix of 216 coupons. Later, Ti-6Al-4V was added to the project, but not to the DOE. The coupons were repaired with like material.

Materials Chosen

From the suggestion of the DoD and OEM representatives, six materials were chosen; all materials that the end users were interested in which appear in almost all gas turbine engines as well as other military and commercial applications. Ti-6Al-4V was later added. The materials are described in Table 1.

Table 1: Specimen and Electrode Materials

Substrate	Specification	Electrode Specification
17-4PH	AMS 5604	AMS 5825
410 SS	AMS 5504	AMS 5823
Hastelloy X	AMS 5754	AMS 5798
Haynes 188	AMS 5608*	AMS 5801
Inconel 625	AMS 5666	AMS 5837
Inconel 718	AMS 5663	AMS 5832
Ti-6Al-4V		

Studies/Testing

Metallurgical Evaluation

Objective

The metallurgical evaluation plan was formulated with several objectives in mind. The primary purpose for these coupon tests was to evaluate both the macrostructure and the microstructure of the ESD repair. Of particular interest were discontinuities (porosity, inclusions, and oxides), coating-substrate bond quality, grain growth, general microstructure, size of structure features and any other notable features. Second, the results of the metallurgical evaluation dictated which ESD parameters and techniques to apply to the mechanical test specimens. Additionally, the processing time and weight gain of the coupons indicated the deposition rate.

Test Preparations

An initial DOE was established which required 36 coupons of each of the six materials (not including Ti-6Al-4V, as it was added late into this project). Flat coupons, 25 mm (1 in.) x 12 mm (0.5 in.) x 6 mm (0.25 in.), were cut from plate material. Defects were created to mimic a typical excavated area in a damaged GTE component. Defects depths averaged .71 mm (0.028 in.) and diameters averaged 8 mm (0.32 in.). Figure 1 shows the prepared coupon.

Figure 1: Metallurgical Specimen

After the defects were created in the coupons, three of the materials were sent for heat treatment, as shown in Table 2.

Table 2: Pre-ESD Heat Treatments

Material	Pre-ESD Heat Treatment
17-4 PH	Age @ 900°F for 1 hr per AMS 2759/3
410 Stainless Steel	Preheat @ 1400°F for 1 hr, Austenitize @ 1800°F for 30 min, Temper @400°F for 2 hr per AMS 2759/5
Hastelloy X	annealed (as received)
Haynes 188	annealed (as received)
Inconel 625	annealed (as received)
Inconel 718	Age @ 1325°F for 8 hr, F/C to 1150 and age @ 1150°F for 18 hr total time per AMS 2774
Ti-6Al-4V	as received

The defects were filled, via the ESD process, with like material, to a height above the original surface (if possible). If build-up did not occur, the repair was typically stopped after 60 minutes. Using the processing time and the change in weight, deposition rates were calculated and recorded. For each coupon, a digital surface photograph was taken. The coupon was then cut slightly off-center through the middle of the repaired area.

Portland State University, in addition to Advanced Surfaces and Processes, performed the metallurgical evaluation on all seven materials. The specimens were mounted in clear Struers Epomet metallographic material, then ground and polished to a 0.05 micron finish. The specimens were micrographed and microhardness tested, then etched by an electrolytic 10% oxalic solution. After etching, additional microscopy was performed.

Test Procedures

The metallographic specimens were examined optically at magnifications between 50x and 1000x with both normal illumination and Normarski Differential Interference Contrast. Scanning Electron Microscopy (SEM) examinations were conducted on two microscopes; an FEI XL FEG/SFEG/Sirion at PSU and a Leo SEM at Battelle National Labs. Transmission Electron Microscopy (TEM) work was conducted on a Tecnai Model F20. Specimens were ion milled with a Focused Ion Beam (FIB) from the interface between the base metal and deposit. This work was performed on a FEI Strata DB 235, Dual Beam Field Emitting SEM by FEI for a select few of the specimens.

Discontinuity measurements were performed with the Media Cybernetics MSQ Ver. 6.51.199 image analysis system at magnification of 200x and 500x, with the 500x values selected for data analyses and comparisons. Recorded data included discontinuities (frequently referred to as "porosity") for each field, the average percent area discontinuities and standard deviation between three and six fields for each specimen.

Results

Microscopy included optical, SEM and TEM micrographs. A few of the more interesting micrographs are presented in Figure 2 through Figure 14.

Figure 2: 17-4 PH #13 at 50x* (Optical)

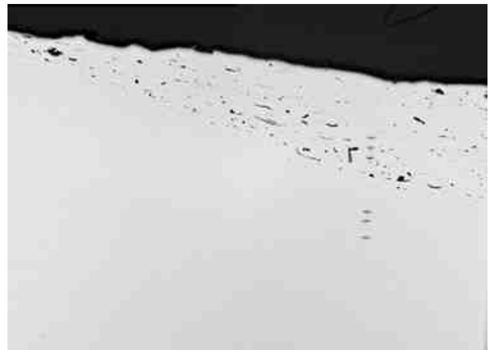

Figure 3: 410 SS #36 at 50x* (Optical)

Figure 4: Hastelloy X #19 at 50x* (Optical)

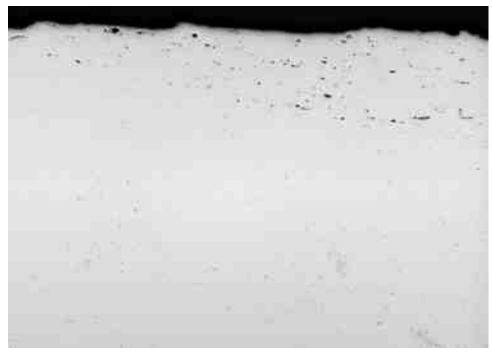

Figure 5: Haynes 188 #07 at 50x* (Optical)

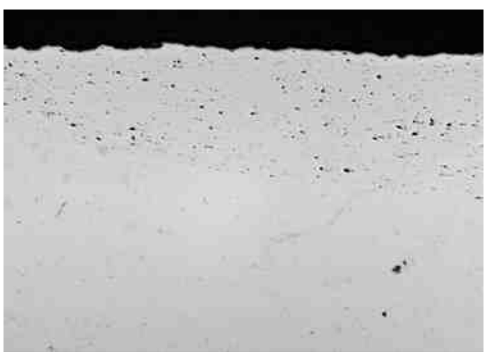

Figure 6: Inconel 625 #33 at 50x* (Optical)

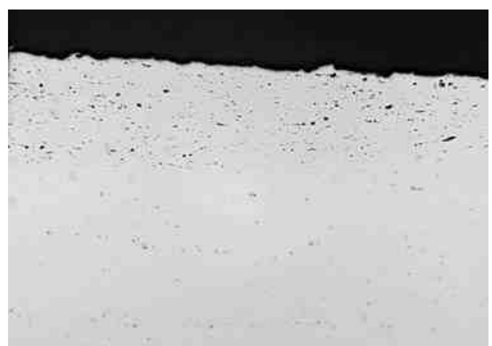

Figure 7: Inconel 718 #33 at 50x* (Optical)

*50X when viewed as a 76 mm (3 in.) by 102 mm (4 in.) image

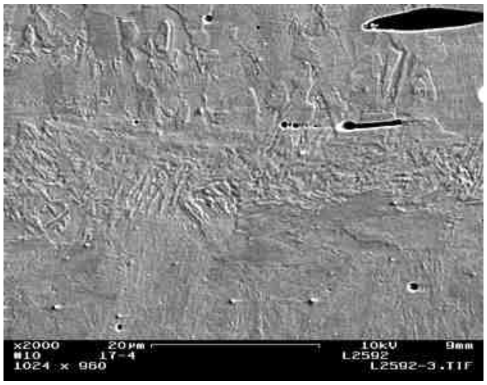

Figure 8: 17-4 PH (SEM)

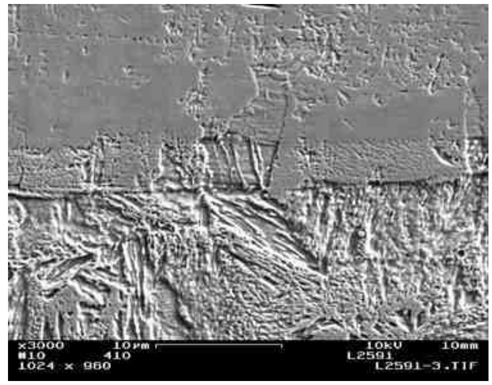

Figure 9: 410 SS (SEM)

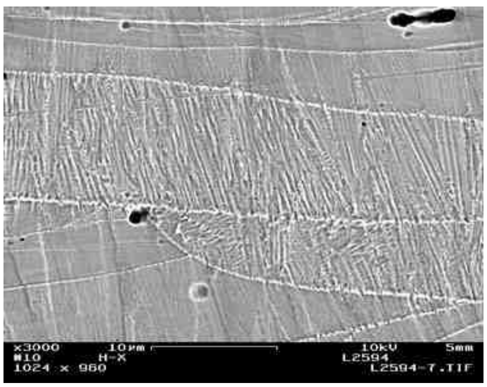

Figure 10: Hastelloy X (SEM)

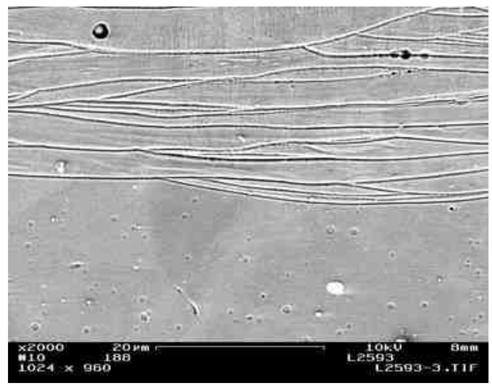

Figure 11: Haynes 188 (SEM)

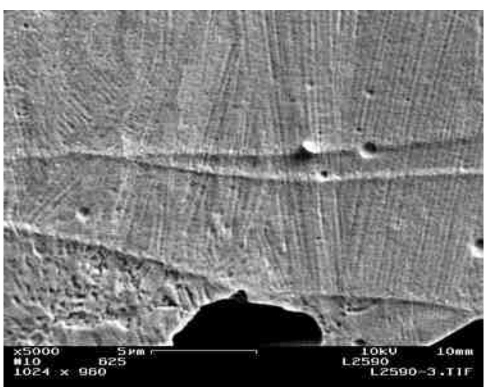

Figure 12: Inconel 625 (SEM)

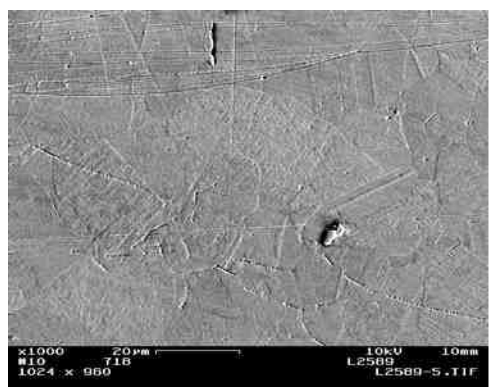

Figure 13: Inconel 718 (SEM)

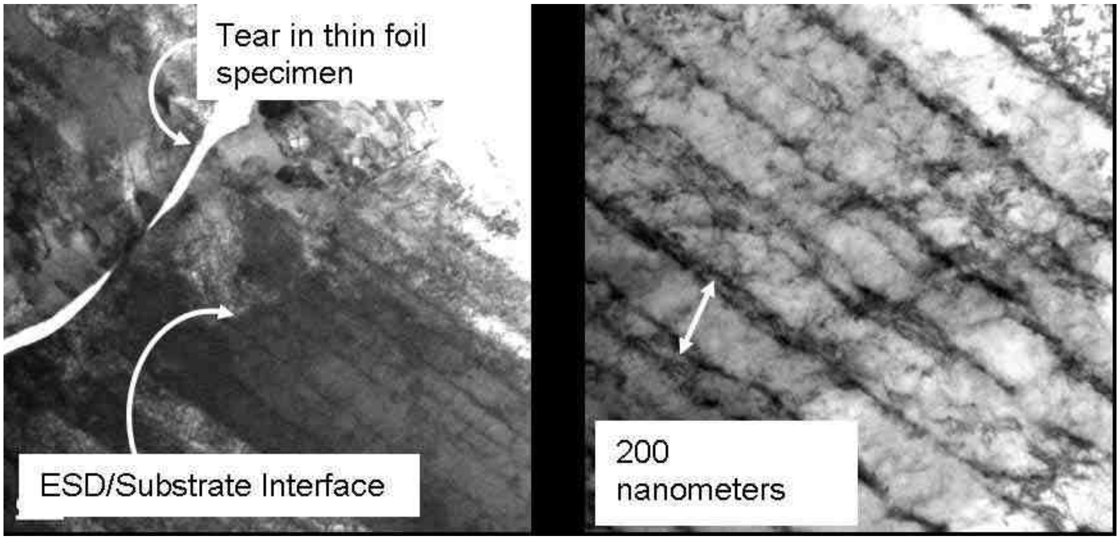

Figure 14: Inconel 718 (TEM)

Discontinuity values are the area percent of dark areas in the metal in each image frame. Dark areas could represent voids, inclusions (like oxides) or polishing artifacts from splat boundaries. No distinction was made on the type, size or shape; all visible dark areas were counted. The six fields were used to produce the specimen average. The standard deviation was recorded to demonstrate scatter of the data. The results of the discontinuities analysis are summarized in Table 3.

Table 3: Discontinuities data summary

Material	Discontinuities Ave Volume (%)			Discontinuities Standard Deviation		
	low	*high*	*average*	*low*	*high*	*average*
17-4 PH	0.67	3.87	1.88	0.04	3.48	0.89
410 SS	0.78	7.26	2.42	0.24	4.73	1.44
Hastelloy X	0.62	4.31	2.19	0.09	3.72	0.60
Haynes 188	0.65	5.86	2.26	0.13	2.76	0.74
Inconel 625	0.39	3.79	1.35	0.18	1.99	0.60
Inconel 718	0.45	3.76	1.41	0.12	2.53	0.80
Ti-6Al-4V	0.10	3.74	1.62	0.43	2.05	0.95

Hardness Testing

<u>*Objective*</u>

Microhardness tests were conducted by Portland State University on all seven materials to determine the hardness of the ESD repair material and compare it to the substrate material. These tests may indicate the wear characteristics of an ESD repair.

Test Preparations

The coupons prepared for metallurgical evaluation, once mounted and polished, were used for the microhardness tests.

Test Procedures

Microhardness testing was conducted in the coatings, the base metal and in the transition between the two. In the transition region microhardness was used to test for heat affected zones (HAZ). Microhardness testing was done with a Struers Duramin microhardness unit at a series of loads between 50 and 1000 grams. The indentations were read on the Duramin microhardness and the MSQ image analysis computers.

Results

Two specimens were tested in the base material; six in the repair area. Two specimens had coatings too thin to test and were excluded from Table 4.

Table 4: Microhardness Test Results

Material	Substrate Hardness (Knoop)	Repair Hardness (Knoop)
17-4 PH	480	274.4
410 stainless steel	509	395.7
Hastelloy X	246	342.2
Haynes 188	292	385.6
Inconel 625	267	363.4
Inconel 718	526	363.8
Ti-6Al-4V	330	383.7

Fatigue Testing

Objective

Fatigue tests were conducted by Edison Welding Institute on Inconel 718 to determine the effects of the ESD process on the substrate material.

Test Preparations

Two sets of Inconel 718 fatigue specimens were tested, six base material specimens and six ESD repaired specimens. The fatigue specimens were produced from 19.0-mm (¾-in.)-round bar with the dimensions described in Figure X. The specimens were subjected to GEAE's 46613GTH/FR-1/03 1 heat treatment. Transverse grooves were machined in one side of the specimen, approximately 0.5-mm (0.020-in.)-deep around the entire circumference of each specimen. The grooves were filled with Inconel 718 via ESD using parameters which appear in welding procedure specifications WPS 6-104-ESD-G-Ni. Multiple layers of filler metal were applied until the entire groove was filled slightly beyond flush with the specimen surface. Final grinding removed the excess ESD buildup as well as ~ 0.1 mm (~ 0.005 in.) of base metal. Extreme care was taken in grinding and polishing the LCF specimens to the requisite surface finish such that residual stresses were not introduced in the test articles that could cause erratic test results. The final dimensions and surface finishes of both base material and ESD repaired specimens were identical. Once repaired, these samples were then re-heat treated using an aging treatment. LCF specimens, as well as Tensile and Bend test specimens are shown in Figure 15.

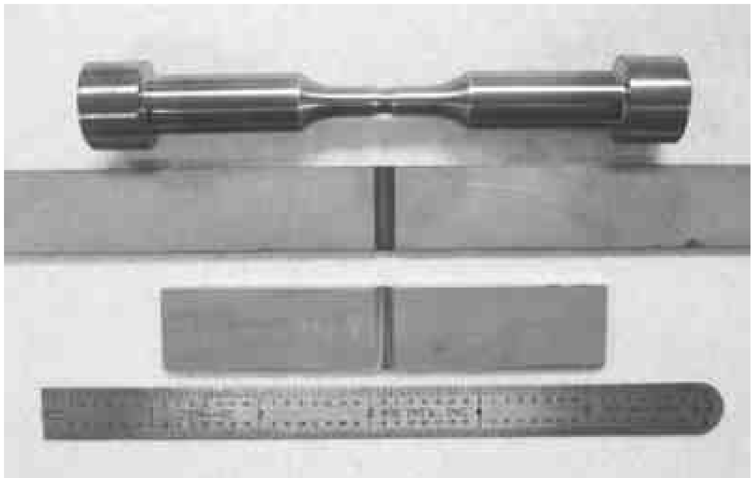

Figure 15: LCF, Tensile and Bend Test Specimens

Test Procedures

The LCF specimens were tested at 1000°F, with a single load range of 690 MPa (100 ksi). The choice of load range was based on recommendations from GEAE who had previously funding a testing program that looked at other lower load ranges for LCF testing. Testing frequency was set at 3 Hz up to 20,000 cycles. At that cycle count, the testing frequency was increased to 20 Hz and testing resumed until ultimate failure or test run-out, pre-established at 1,000,000 cycles. The load amplitude ratio (Ra) for all LCF testing was set at a value of Ra = 0; the specimens were cycled between a minimum load of 0 MPa (0 ksi) and a maximum load of 100 MPa (690 ksi). Both the base material and ESD repaired specimens were tested using identical conditions so that test results could be directly compared.

Results

The results of LCF testing are summarized in Table 5.

Table 5: Summary of LCF Results

Base material	***ESD repaired material***	***Ratio of the average repaired versus average base material***
1,000,000 cycles	416,500 cycles	42%

Tensile Testing

Objective

Tensile tests were conducted by Edison Welding Institute on Inconel 718 to compare the stress-strain curves, ultimate tensile stress, yield stress and percent elongation of an ESD repaired material to base material.

Test Preparations

Two sets of Inconel 718 tensile specimens were tested, six base material specimens and six ESD repaired specimens. The tensile specimens were machined from 3.2-mm (0.125-in.)-thick plate. The specimens were subjected to GEAE's 46613GTH/FR-1/03 1 heat treatment. Transverse grooves were machined in one side of the specimen, approximately 0.5-mm (0.020-in.) deep. The grooves were filled with Inconel 718 via ESD using parameters which appear in welding procedure specifications WPS 7-104-ESD-G-Ni. Multiple layers of filler metal were applied until the entire groove was filled slightly beyond flush with the specimen surface. Final grinding removed the excess ESD buildup as well as ~ 0.1 mm (~0.005 in.) of base metal. The final dimensions and surface finishes of both base material and ESD repaired specimens were identical. Once repaired, these samples were then re-heat treated using an aging treatment. Tensile test specimens, as well as LCF and Bend test specimens are shown in Figure 15.

Test Procedures

Tensile specimens were tested at 1000°F, according to the standard guidelines of ASTM E8.

Results

The results of Tensile testing are summarized in Table 6.

Table 6: Summary of Tensile Test Results

	Base material	ESD repaired material	Ratio of the average repaired versus average base material
Tensile strength	189.2 ksi	169.1 ksi	89 %
Yield strength	156.0 ksi	158.4 ksi	102 %
Percent elongation	17.6 %	4.9 %	28 %

Bend Testing

Objective

Bend tests were conducted by Edison Welding Institute on Inconel 718 to qualitatively evaluate the strength of the repair between the substrate and the ESD deposit.

Test Preparations

Six Inconel 718 bend samples were prepared; three face bends and three root bends. The bend specimens were machined from 3.2-mm (0.125-in.)-thick plate and subjected to GEAE's

46613GTH/FR-1/03 1 heat treatment. Transverse grooves were machined in one side of the specimen, approximately 0.5-mm (0.020-in.) deep. The grooves were filled with Inconel 718 via ESD using parameters which appear in welding procedure specifications WPS 8-104-ESD-G-Ni. Multiple layers of filler metal were applied until the entire groove was filled slightly beyond flush with the specimen surface. The ESD deposit was manually ground flush with the adjacent base metal. Once welded, these samples were then re-heat treated using an aging treatment. Bend test specimens, as well as Tensile and LCF test specimens are shown in Figure 15.

Test Procedures

Based on industry information, the basic design criteria for this material is a requirement of 2% minimum elongation. To achieve that level in the 3.2-mm (0.125-in.) thick specimens, they were bent around a mandrel having a diameter of 156 mm (6.125 in.). Since all bend specimens passed the 2% elongation bend test, it was decided to subject them to more extreme conditions by bending the already bent specimens around a 76 mm (3 in.)diameter mandrel and evaluate the results of 4% elongation. Figure 16 shows the side view of a typical bend specimen.

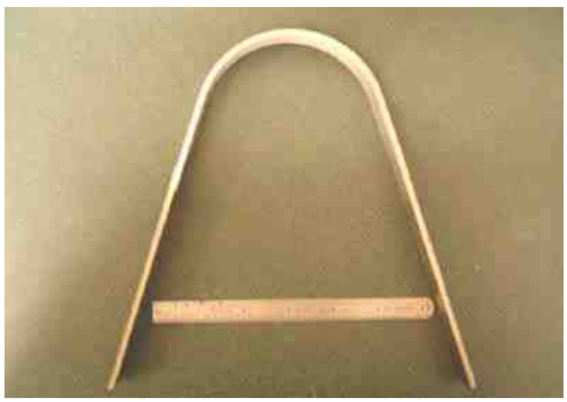

Figure 16: Side View of Typical Bend Specimen with 4% Elongation

Results

All specimens passed the 2% elongation bend test. When subjected to 4% elongation, all three root bend passed. Two of the three face bend specimens exhibited rejectable indications, attributable to operator error.

Summary

This initial testing has demonstrated that low porosity ESD repairs can be achieved with the ESD process. The discontinuities of a manually applied ESD layer are less than 5% by area.

While the process is slow, deposition rates as high as 44.3 mg/min were seen for the Haynes 188 material. However, deposition rate alone should not be the basis for selecting ESD as a viable repair. The entire component repair time, including fixturing, masking, post heat treat, post machining, etc. should be included when comparing the ESD process to other processes.

Hastelloy X, Haynes 188, Inconel 625 and Ti-6Al-4V demonstrated an increase in hardness of the ESD repair material over the base materials. 17-4 PH, 410 stainless and Inconel 718 were not as hard as the parent material. This is to be expected for the precipitation hardened materials.

During fatigue testing, several anomalies occurred. First, two of the unwelded samples failed prematurely at the grip; these were considered "no tests" and were not included in the results. There was also significant scatter from the welded samples. In a previous test program, the ratio of welded to unwelded was only 14%, so this set of specimens exhibited a threefold increase.

After repair and final machining, nearly 25% of the tensile specimen cross sections were comprised of ESD applied metal. Consequently, any strength values greater than 75% of the values obtained from the base material samples are indications that the ESD deposits are positively contributing to load-carrying capacity. Further, there is actually an increase in yield strength, which is the primary design criterion for load capacity.

All specimens passed the 2% elongation bend test. When subjected to 4% elongation, all three root bend passed. Two of the three face bend specimens exhibited rejectable indications, attributable to operator error.

Future Work

With the extension of this project, a detailed Joint Test Protocol is being developed, including another DOE designed to optimize the ESD parameters and techniques. Future studies will include the execution of a full demonstration plan, to include additional testing performed on specimens repaired with both like and non-like material and on specimens coated with non-ESD coatings. Additional mechanical tests will be conducted, as prescribed in the JTP. All efforts are to qualify ESD as a viable solution for repair of gas turbine engine components.

Acknowledgments

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