Results of materials testing for

ElectroSpark Deposition

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HCAT Program Review Meeting
Hilton San Diego Resort
1775 East Mission Bay Drive
San Diego, CA 92109
# Results of materials testing for ElectroSpark Deposition

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History

Project Began
October 1, 2001

HCAT
February, 2002
Orlando, FL

HCAT
September, 2002
Toronto, Canada

HCAT
April, 2003
San Diego, CA

HCAT
November, 2003
Cape Canaveral, FL

HCAT
July, 2004
Park City, UT

HCAT
March, 2005
Greensboro, NC

HCAT
January, 2006
San Diego, CA

2001
ONDJFMAMJJASONDJFMAMJJASONDJFMAMJ

Phase 1

2002

2003
ONDJFMAMJJASONDJFMAMJJASONDJFMAMJ

Phase 2

2004
ONDJFMAMJJASONDJFMAMJJASONDJFMAMJ

Phase 3

2005
ONDJFMAMJJASONDJFMAMJJASONDJFMAMJ

Continuation

2006
ONDJFMAMJJASONDJFMAMJ

Project Ends
March, 2006

PEWG
February, 2002
San Diego, CA

PEWG
July, 2002
Cincinnati, OH

PEWG
June, 2003
New Orleans, LA

PEWG
April, 2004
Summerlin, NV

PEWG
January, 2005
Myrtle Beach, SC

PEWG
August, 2005
Portland, OR
Project Objective

The goals of this project are to **demonstrate and validate** ElectroSpark Deposition (ESD) as technically feasible and commercially viable for a production-scale process, and to perform the tests necessary to transition ESD for use on gas turbine engine components.
Participants

- ESTCP/HCAT
- PEWG
- Portland State University
- Edison Welding Institute
- Rowan Technology Group
- Pacific Northwest National Lab
- Air Force Research Lab
- Metcut
- Hamilton Sundstrand
- General Electric Aircraft Engines
- Pratt & Whitney
- Tinker AFB
Milestones

- Materials
- Optimization of ESD
- ESD/Robotics/UIT
- Joint Test Protocol
- ESD on Chrome Plate
- Components

HCAT Member WorkSpace → ESD → Test Plans → Demonstration Plan
What is ESD?

The ESD process is a capacitive discharge micro-arc process using a consumable electrode. The electrode and substrate materials are melted, rapidly solidify, and build-up occurs incrementally.

- Metallurgical bond
- Low heat input
- Rapid solidification
- No pre-ESD preparation
- No post-ESD processing
- Environmentally benign
- Portable
- Applicable for NLOS
Materials

- Inconel 718 (Optical)
- Inconel 718 (TEM)
- ESD/Substrate Interface
- 410 stainless steel (SEM)

- Hastelloy X
- 17-4 PH
- Haynes 188
- IN 625
- IN 718
- 410 SS
- Ti-6Al-4V

January 26, 2006
Discontinuities and $\mu$-hardness

<table>
<thead>
<tr>
<th>Material</th>
<th>Discontinuities Average Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-4 PH</td>
<td>1.88</td>
</tr>
<tr>
<td>410 SS</td>
<td>2.42</td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>2.19</td>
</tr>
<tr>
<td>Haynes 188</td>
<td>2.26</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>1.35</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>1.41</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>1.62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Substrate Hardness (Knoop)</th>
<th>Repair Hardness (Knoop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 718</td>
<td>526</td>
<td>363.8</td>
</tr>
<tr>
<td>17-4 PH</td>
<td>480</td>
<td>274.4</td>
</tr>
<tr>
<td>410 SS</td>
<td>509</td>
<td>395.7</td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>246</td>
<td>342.2</td>
</tr>
<tr>
<td>Haynes 188</td>
<td>292</td>
<td>385.6</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>267</td>
<td>363.4</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>330</td>
<td>383.7</td>
</tr>
</tbody>
</table>
Optimization

- **Materials of Interest**
  - IN718 on IN 718
  - 410 SS on 410 SS
  - Ti-6Al-4V on Ti-6Al-4V
  - IN 625 on chrome plated IN 718

- **DOE Optimization**
  - Deposition Rate
  - Microhardness
  - Porosity

- **Parameters Selected for Execution of Joint Test Protocol**

- Added UIT
Objective: Demonstrate improvement in quality and production rates of an ESD repair on IN718 through automation and ultrasonic impact treatment (UIT).
ESD, Robotics and UIT

Improvement in ESD

Automated with UIT vs. Manual

<table>
<thead>
<tr>
<th>Metric</th>
<th>Automated</th>
<th>Manual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Deposition Rates</td>
<td>11 X</td>
<td></td>
</tr>
<tr>
<td>Discontinuities</td>
<td>0.8 X</td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>1.3 X</td>
<td></td>
</tr>
</tbody>
</table>
\( \mu \)-hardness with UIT

IN 718 on IN 718
6 ESD layers
Indents 0.005” apart
Top ESD noUIT

1 - B 200x hardnesses ——— 75 micron
Discontinuities with UIT

![Manual](image1)

![Automated + UIT](image2)

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**Average Volume (%)**

- Manual IN 718
- Initial UIT
- Optimized UIT

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Deposition Rate with UIT
Joint Test Protocol

- Pin on Disk Wear
- Fatigue
- Residual Stress
- Corrosion
- Adhesion Bond
- Tensile
- Hamilton Sundstrand Wear
Pin on Disk Wear

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum Groove Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Metal</td>
</tr>
<tr>
<td>2-1 (V4)</td>
<td>114</td>
</tr>
<tr>
<td>2-2 (V4)</td>
<td>92</td>
</tr>
<tr>
<td>2-4 (#32)</td>
<td>128</td>
</tr>
<tr>
<td>2-3 (#32) long test</td>
<td>218</td>
</tr>
</tbody>
</table>
Fatigue

![Fatigue Test Setup]

![Test Specimen]

**Graph:**
- **X-axis:** Cycles to Failure
- **Y-axis:** Maximum Stress (psi)
- Legends:
  - Baseline
  - Divot
  - Bead on Plate
  - #32
  - V4
  - UIT

Data points for each condition are plotted on the graph, showing the relationship between cycles to failure and maximum stress for different materials and treatments.
Fatigue

![Fatigue Graph]

- **Baseline**
- **Baseline with Divot**

**Axes:**
- **Y-axis:** Maximum Stress (psi)
- **X-axis:** Cycles to Failure

**Legend:**
- Blue diamond: Baseline
- Pink square: Baseline with Divot
Fatigue

![Fatigue Graph]

- **Baseline**
- **Baseline with Divot**
- **ESD #32**

- Maximum Stress (psi)
- Cycles to failure

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Fatigue

![Fatigue Graph]

- Baseline
- Baseline with Divot
- ESD V4

Maximum Stress (psi) vs. cycles to failure
Fatigue

![Fatigue Graph]

- **Baseline**
- **Baseline with Divot**
- **Bead on Plate**

- **Maximum Stress (psi)** vs **cycles to failure**
Fatigue

Baseline
Baseline with Divot
ESD + UIT

cycles to failure

Maximum Stress (psi)

0 20000 40000 60000 80000 100000 120000 140000 160000 180000 200000

10,000 100,000 1,000,000 cycles to failure
Fatigue Debit (% of Baseline)

Low Cycle fatigue - ESD repairs in IN 718

- Divot
- ESD #32
- ESD V4
- ESD #32 + UIT
- ESD #32 Bead on Plate

Baseline
The objective of including residual stress analysis in the JTP was to obtain an indication of the presence of residual stresses due to the ESD process.

Results: Tensile stresses with ESD, Higher tensile stresses with increased energy (V4).
Corrosion

ASTM B117 performed
Adhesion Bond

ASTM C 633 performed
Tensile

- **Tensile Strength**
- **Yield Strength**
- **Reduction in Area**
- **Elongation**
Hamilton Sundstrand Wear

<table>
<thead>
<tr>
<th>Short stroke (fretting)</th>
<th>Long stroke (sliding)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 and S12 Baseline</td>
<td>S2 and S13 Baseline</td>
</tr>
<tr>
<td>N1 #32 + UIT</td>
<td>N3 V4</td>
</tr>
<tr>
<td>N2 #32</td>
<td>N4 #32 + UIT</td>
</tr>
<tr>
<td>N5 V4</td>
<td>N6 #32</td>
</tr>
</tbody>
</table>

Weight Loss (g)

- Short stroke (fretting)
  - S2 and S13: Baseline
  - N4: #32 + UIT
  - N6: #32

- Long stroke (sliding)
  - S1 and S12: Baseline
  - N1: #32 + UIT
  - N2: #32
  - N5: V4

Panel Specimen

Flat Counter-face Specimens
Chrome Repair

Into the substrate
Chrome Repair

In the chrome only - scratches

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Strip and Rechrome

ESD fill → Resurface
Strip → Resurface
Rechrome → FPI
Chrome Particle Emissions

The ESD repair of chromium (EHC) does produce fine particulate of metallic chromium and hexavalent chromium.

At 6” and 12”, up to 5 micrograms were measured.

No hexavalent chromium was found at the face level, even after collection of 1 cubic meter of air (8+ hours of exposure).
From Material Properties
To Components

#5 Bearing Housing (410 SS)
Stator Segment (IN 718)
Compressor Rear Shaft (Chrome Plate)
#5 Bearing Housing

P/N 712141
TF 33
AMS 5613
(410 stainless steel)
#5 Bearing Housing

Excavate the defective area

Fill with ESD

Blend to original surface
#5 Bearing Housing

Stator Segment 10-12 Stage

P/N 4077880
F100 – 229
Inconel 718
Stator Segment 10-12 Stage

>0.005” deep wear in hook
non-line-of-sight

Current repair:
Cut off hook,
weld on new,
heat treat part

no repair if the part has met
permissible heat treat cycles
Stator Segment 10-12 Stage

Hardness same as parent material

Wear resistant to "chattering"

ESD repair technique complete
Compressor Rear Shaft

P/N 9103M58G12
TF 39
Inconel 718
In Summary

- Joint Test Report

HCAT Member WorkSpace → ESD → Test Plans → Demonstration Plan

Implementation
Results of materials testing for ElectroSpark Deposition

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