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IN-HOUSE WELDING STUDIES SUPPORTING THE PRELAUNCH ASSESSMENT OF THE STS-6 MAIN ENGINES

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June 1983
This memorandum describes two in-house welding studies undertaken by the Materials and Processes Laboratory as a result of problems with the Challenger engines.

(1) Heat Exchanger Coils: Description of process used to perform these welds, sample test data, recommendations for process improvement.

(2) Weld 56; High-Pressure Fuel Turbo Pump: Description of effort to simulate problem welds, as well as good welds, test data, and conclusions.

**Abstract**

**Keywords**

STS-6 Prelaunch Assessment - EH
HEX/Weld 56 HPFTP Studies

**Distribution Statement**

Unclassified - Unlimited
ACKNOWLEDGMENT

Many people played significant roles in the performance of these studies. Without the cooperation of each of them, these results could not have been obtained.

Members of the Advanced Manufacturing Technology Laboratory (MMA) who contributed significantly to the effort were Charles Brosemer and Joe Sexton. Members of the Metals Processes Branch, and the Metallurgy Research Branch of the Materials and Processes Laboratory (MSFC) who contributed significantly to the effort were Paul Munafo, Newton Tiller, Ed White, Ernie Bayless, Jack Reid, Sam Clark, and Terry Craig.

Because many people were involved in this effort, it is possible that these acknowledgments may overlook someone. Such omission is unintentional, and we wish to extend our thanks to all those who made a contribution.
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>AN EVALUATION OF THE WELDING PROCESS USED IN FABRICATION OF THE HEAT EXCHANGER COILS</td>
<td>1</td>
</tr>
<tr>
<td>A SIMULATION OF WELD 56 IN THE HIGH PRESSURE FUEL TURBO PUMP TURNAROUND DUCT</td>
<td>3</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>4</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Specimen configuration</td>
</tr>
<tr>
<td>2.</td>
<td>Weld insert configuration</td>
</tr>
<tr>
<td>3.</td>
<td>Initial components</td>
</tr>
<tr>
<td>4.</td>
<td>Finished specimen</td>
</tr>
<tr>
<td>5.</td>
<td>Weld station set-up</td>
</tr>
<tr>
<td>6.</td>
<td>Calibrated flow-meter</td>
</tr>
<tr>
<td>7.</td>
<td>Radiography: HEX coils</td>
</tr>
<tr>
<td>8.</td>
<td>Electrode configuration</td>
</tr>
<tr>
<td>9.</td>
<td>Weld fixture</td>
</tr>
<tr>
<td>10.</td>
<td>Fixture-tube assembly, 1</td>
</tr>
<tr>
<td>11.</td>
<td>Fixture-tube assembly, 2</td>
</tr>
<tr>
<td>12.</td>
<td>S-N data: HEX specimens</td>
</tr>
<tr>
<td>13.</td>
<td>HEX weld specimen test summary</td>
</tr>
<tr>
<td>14.</td>
<td>Summary of weld 56 test data</td>
</tr>
<tr>
<td>15.</td>
<td>Radiography: weld 56</td>
</tr>
<tr>
<td>16.</td>
<td>Radiography: weld 56</td>
</tr>
<tr>
<td>17.</td>
<td>Radiography: weld 56</td>
</tr>
<tr>
<td>18.</td>
<td>Radiography: weld 56</td>
</tr>
</tbody>
</table>
INTRODUCTION

Subsequent to the problems occurring in the Challenger main engines, which resulted in a delay in STS-6 launch, two welding studies were undertaken by the Materials and Processes Laboratory of Marshall Space Flight Center in an attempt to suggest possible solutions to these problems.

The first study involved investigation of the process used by Wintec to weld the heat exchanger coils. The second involved simulation of the weld 56 joint in the high pressure fuel turbo pump. These two in-house welding studies are summarized in this report.

AN EVALUATION OF THE WELDING PROCESS USED IN FABRICATION OF THE HEAT EXCHANGER COILS

The leak in the heat exchanger of Challenger engine 2016 stimulated program-wide examinations. Since the heat exchanger was known to fail due to lack of fusion in a weld, the welding procedures were of particular interest. Metals Processes Branch at MSFC fabricated several test specimens which closely represent the heat exchanger coil. Tubes of 316 stainless steel and Haynes 188 alloy were joined together with a filler insert. The configurations of the test specimens and the filler insert are shown in Figures 1 and 2, respectively. Figure 3 shows the initial components, and Figure 4 shows a completed specimen.

The welding system set-up is shown in Figure 5. The fixture and welding positioner proved to be very important in providing the necessary accessibility and controlled travel speed. Because the amperage used to weld was very low (3 to 4 amps), a sensitive ammeter was required to effectively record it. A helium flow meter was calibrated for determination of the argon shield gas flow (Figure 6), because an argon flow meter capable of measuring small flow rates was unavailable. The purge and back-up gas was fed into the inside diameter (ID) by means of an injector needle which acted as a sliding bearing to avoid tangling the gas lines. Finally, the weldor used a "hand grip" to hold the torch steady along the seam of the joint.

The following factors were evaluated during the investigation:

1) The effect of tack weld oxidation on weld quality
2) The effects of electrode configuration
3) The purge and back-up gas shielding requirements
4) Fixturing and accessibility
5) Weld process variables
The following observations were made: If the inert gas shield is removed from
the tack weld before it cools, the tacks will interfere with metal flow, creating a flaw
as noted in Figure 7, Specimen No. 3. Also, if any cracks occur in the tacks, they
will remain in the final weld.

The configuration of the electrode proved to be critical. A 0.040 in. diameter
thoriated tungsten electrode was tapered for a length of 5/16 to 3/8 in. Our observ-
ations showed that, when the tip of the electrode was left sharp, a ball of hot molten
metal formed on the tip of the electrode, causing the arc to wander along the surface
of the ball. When the tip of the electrode was somewhat blunted, this problem was
solved. Figure 8 shows the tapered electrode before and after blunting.

An inert gas shield was required for both inside and outside diameters of the
tubes. ID shielding was provided by means of the calibrated helium flowmeter at 0.75
CFH. A flow rate of 15 CFH was used for shielding the weld arc.

The fixture was necessary to hold the parts in place and to provide proper fit-up
of the joint. Improper fixturing was suspected to be responsible for thin spots of the
parent materials. Improper fit-up caused a portion of the tube wall to be
removed in the post-weld reaming operation. Due to lack of sufficient data points,
MSFC is unable to recommend an alternative to reaming at this time. Investigation
into improved fixturing should be undertaken.

A rubber O-ring was added to the fixture to provide a spring action to maintain
fit-up throughout the welding process.

The welding positioner provided needed accessibility by allowing the operator to
rotate the assembly at a controlled speed. Figures 9 through 11, respectively, show
the fixture, the fixture-tube assembly, and the entire assembly in place on the
fixture.

Proper voltage, amperage, and travel speed are necessary to insure any good
weld. Our data point observations showed the following set of parameters to be
optimal:

Travel Speed: 0.324 IPM (0.275 RPM)
Voltage: 14 to 15 V
Amperage: 3.50 (+0.50 - 0.00) A

These parameters differed from the following, which were used by Wintec.

Travel Speed: 10 RPM
Voltage: Not specified except as Low Range Voltage
Amperage: 3 to 32 A

In addition, the shield and purge gas flow rates differed from our recommenda-
tions, as did the configuration of the electrode. Wintec used a shield gas flow rate
of 40 CFH and a purge gas flow rate of 7 CFH. The electrode was tapered, but not
blunted.

A total of seven test specimens were fabricated at MSFC. Two of the specimens
were tested in tension, and failed at an average of 83.9 Ksi. These data compare
favorably with the handbook design values of 30 Ksi for yield strength, and 80 Ksi for
ultimate strength of 316 stainless. This indicates that there is not a metallurgical
problem in the welding of 316 stainless to Haynes 188 when it is welded according to
the procedures outlined in this report. The remaining five specimens were evaluated in high-cycle fatigue, with a stress ratio of 0.05 (Stress ratio = Minimum stress/Maximum stress). Most of the specimens failed at the edge of the weld in the Haynes 188 material. Data for these tests are plotted in Figure 12.

Figure 13 lists X-ray defects and mechanical test results for each specimen. From Figures 12 and 13, it can be seen that radiography is an accurate indicator of most serious weld defects (such as the large lack of penetration seen in Specimen No. 3, Figure 7), but that less evident defects, such as restricted metal flow (see Specimen No. 6, Figure 7), are difficult to determine by radiography. In this limited data sample, there appears to be no good correlation between radiographic results and mechanical test data. Consistent with our experience on other programs, X-ray inspection alone is not adequate to determine overall weld quality.

In addition to the improved parameters developed at MSFC, it is our opinion that the process could be further improved by automation. Both Rocketdyne and Wintec are considering systems that would make the process semi-automatic, with the operator interceding only when it is necessary to change the weld parameters. This system should increase process control and improve the quality of the welds.

A SIMULATION OF WELD 56 IN THE HIGH PRESSURE FUEL TURBO PUMP TURNAROUND DUCT

MSFC also conducted a series of tests to assess the acceptability of weld 56 in the high pressure fuel turbo pump (HPFTP) turnaround duct on two Challenger engines. This study was prompted when post-assembly X-ray of these welds revealed intermittent lack of penetration around the circumference.

The test program included weld specimens configured to the joint dimensions used on the Challenger engines and the anomalous dimensions used on engine 2015 which failed in test. Attempts were made both to fully penetrate the joint and to simulate a condition in which the joint could be "bridged" but not fully penetrated.

The specimen weld beads were ground, etched, penetrant-inspected from the crown side, and X-rayed. Following non-destructive testing, photomacrographs were taken to determine the depth of weld penetration associated with each set of welding conditions.

"Bridging" was easily achieved by feeding in excess filler wire to cool the arc and limit penetration. Visual and surface inspection of the bridged specimens indicated the welds were acceptable, but sections revealed lack of penetration in several cases (Figure 16, Specimens 2a and 3). There was also a lack of penetration noted during sectioning of specimens where weld shrinkage pulled the unfused region of the joint into a very tight crack. Radiography had failed to reveal this problem (Figure 16, Specimens 1a and 2b). An incidental finding was that there appears to be a high potential for residual stress in these joints, as evidenced by the "buckling" of the thinner material in the specimens shown in Figure 16.

Welds simulating the reverse taper of the anomalous 0210R4 joint presented problems. These specimens required a higher welding current (40 to 50 amps) to fully penetrate the joint. Mismatch was also a problem, approaching 100 percent at times. The mismatch was apparently caused when the thinner member slid down the chamfer ahead of the weld.
Figure 14 summarizes the results of all the tests conducted at MSFC. Rocketdyne's "as-welded" allowable ultimate tensile strength is 102 Ksi. Note that the ultimate strength of the specimens was fairly consistent with percent penetration. Fatigue strength is expected to follow the same pattern. Figures 15 through 18 are included for reference.

CONCLUSIONS

Investigation of the welding process used by Wintec on the Challenger engines' heat exchanger coils revealed an unacceptable procedure. Automation of the procedure and use of NDE methods other than radiography are recommended.

Two automatic welding systems are currently being considered for adaptability to the heat exchanger weld process. If automation is not achieved, improved fixturing to reduce the possibility of reamer damage to the parent metal is recommended.

An investigation into new NDE techniques which could be applied to the heat exchanger coils is currently underway at Wintec.

Simulation of the weld 56 joint on the HPFTP revealed a number of constraints on the weldor as well as a procedure that is difficult to follow, resulting in inconsistent welds. In addition, NDE procedures used to date have not been sufficient to detect unfused regions of the joint. In view of these findings, it is recommended that this joint be reviewed by design and manufacturing.
Figure 1. Specimen configuration.
Figure 2. Weld insert configuration.
Figure 3. Initial components.
Figure 4. Finished specimen.
Figure 5. Weld station set-up.
Figure 6. Calibrated flow-meter.
Figure 7. Radiography: HEX coils.
Figure 8. Electrode configuration.
Figure 9. Weld fixture.
Figure 12. S-N data: HEX specimens.

NOTES:
1. R = +0.05
2. Rate = 40 Hz (appr.)
3. Stress area based on minimum area @ weld interface
4. Numbers in parentheses are specimen numbers.
<table>
<thead>
<tr>
<th>SPECIMEN NUMBER</th>
<th>RADIOGRAPHY DEFECTS</th>
<th>TEST TYPE/ RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ream damage to both parent materials.</td>
<td>Tensile /83.1 KSI</td>
</tr>
<tr>
<td>2</td>
<td>Small lack of penetration, Ream damage to both parent materials.</td>
<td>Tensile/84.8 KSI</td>
</tr>
<tr>
<td>3</td>
<td>Large lack of penetration</td>
<td>Fatigue/4.3 x $10^4$ cycles @ 27.5 KSI</td>
</tr>
<tr>
<td>4</td>
<td>Restricted metal flow</td>
<td>Fatigue/1.0 x $10^7$ cycles @ 25 KSI</td>
</tr>
<tr>
<td>5</td>
<td>Ream damage in both parent materials, Small lack of penetration.</td>
<td>Fatigue/4.4 x $10^5$ cycles @ 30 KSI</td>
</tr>
<tr>
<td>6</td>
<td>Badly restricted metal flow</td>
<td>Fatigue/1.6 x $10^5$ cycles @ 35 KSI</td>
</tr>
<tr>
<td>7</td>
<td>No evident problems</td>
<td>Fatigue/9.5 x $10^4$ cycles @ 40 KSI</td>
</tr>
</tbody>
</table>

Figure 13. HEX weld specimen test summary.
<table>
<thead>
<tr>
<th>SPECIMEN NUMBER &amp; CONFIGURATION</th>
<th>RADIOGRAPHY</th>
<th>DYE PENETRANT</th>
<th>MACRO (% PENETRATION)</th>
<th>ULTIMATE STRENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1A: Bridge Groove</td>
<td>OK</td>
<td>OK</td>
<td>50%</td>
<td>80.5 Ksi</td>
</tr>
<tr>
<td>#1B: Good Weld</td>
<td>OK</td>
<td>2 Small Pores</td>
<td>100%</td>
<td>147.3 Ksi</td>
</tr>
<tr>
<td>#2A: Penetrate Groove Only</td>
<td>LOP</td>
<td>OK</td>
<td>30%</td>
<td>98.7 Ksi</td>
</tr>
<tr>
<td>#2B: Bridge Groove</td>
<td>LOP</td>
<td>OK</td>
<td>40%</td>
<td>92.9 Ksi</td>
</tr>
<tr>
<td>#3: Bridge Groove</td>
<td>Porosity, LOP</td>
<td>8 Pores</td>
<td>12% (30%)*</td>
<td>71.9 Ksi</td>
</tr>
<tr>
<td>#4: Good Weld</td>
<td>1 Inclusion</td>
<td>OK</td>
<td>100%</td>
<td>147.1 Ksi</td>
</tr>
<tr>
<td>#5: Good Weld</td>
<td>Suspect LOP</td>
<td>OK</td>
<td>100%</td>
<td>144.1 Ksi</td>
</tr>
<tr>
<td>#6: Penetrate .015&quot;</td>
<td>Porosity, LOP</td>
<td>OK</td>
<td>70%</td>
<td>88.0 Ksi</td>
</tr>
<tr>
<td>#7: Bridge Groove</td>
<td>Heavy LOP</td>
<td>1 Pore</td>
<td>40%</td>
<td>76.4 Ksi</td>
</tr>
<tr>
<td>#8: Good Weld</td>
<td>OK</td>
<td>OK</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

* #3: Penetration was 12% on macro, 30% on specimen fracture surface

Figure 14. Summary of weld 56 test data.
Figure 15. Radiography: weld 56.
Figure 16. Radiography: weld 56.
Figure 17. Radiography: weld 56.
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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

ROBERT J. SCHWINGHAMER
Director, Materials and Processes Laboratory