A Space Shuttle Reaction Control System (RCS) thruster failed during a firing test at the NASA White Sands Test Facility (WSTF), Las Cruces, New Mexico. The firing test was being conducted to investigate a previous electrical malfunction. A number of cracks were found associated with the fuel closure plate/injector assembly (Fig 1). The firing test failure generated a flight constraint to the launch of STS-133. A team comprised of several NASA centers and other research institutes was assembled to investigate and determine the root cause of the failure. The JSC Materials Evaluation Laboratory was asked to compare and characterize the outboard circumferential electron beam (EB) weld between the fuel closure plate (Titanium 6Al-4V) and the injector (Niobium C-103 alloy) of four different RCS thrusters, including the failed RCS thruster.

Several metallographic challenges in grinding/polishing, and particularly in etching were encountered because of the differences in hardness, ductility, and chemical resistance between the two alloys and the bimetallic weld. Segments from each thruster were sectioned from the outboard weld. The segments were hot-compression mounted using a conductive, carbon-filled epoxy. A grinding/polishing procedure for titanium alloys was used [1]. This procedure worked well on the titanium; but a thin, disturbed layer was visible on the niobium surface by means of polarized light.

Once polished, each sample was micrographed using bright field, differential interference contrast optical microscopy, and scanning electron microscopy (SEM) using a backscatter electron (BSE) detector. No typical weld anomalies were observed in any of the cross sections. However, areas of large atomic contrast were clearly visible in the weld nugget, particularly along fusion line interfaces between the titanium and the niobium. This prompted the need to better understand the chemistry and microstructure of the weld (Fig 2). Energy Dispersive X-Ray Spectroscopy (EDS) was used to confirm the chemical composition of the variations in contrast in these areas.

Niobium alloys generally require exposure to more aggressive chemical reagents than titanium alloys for etching because of niobium’s chemical resistance; therefore, the titanium portion of the sample was etched first. A five second immersion in Kroll’s reagent revealed a general microstructure on the titanium portion of the sample; however, the titanium heat affected zone closest to the weld, was over-etched due to higher concentrations of refined grains and an increase in beta-phase. The Kroll’s etchant also revealed some microstructure in the weld nugget itself; the niobium portion of the sample remained unetched.

Several niobium etchants were tried on a test piece of niobium C-103, with ASTM E407-161 yielding the best results [2]. The ASTM E407-161 etchant was then used on the thruster EB welds with good results for the niobium; the titanium was significantly over-etched.
To provide investigators with a continuous view of general microstructure across all three distinct regions (weld and parent alloys), the sample was then reground, repolished, lightly etched using Kroll’s reagent, and vibropolished in preparation for Electron Back-Scatter Diffraction (EBSD) mapping. EBSD provided an excellent, continuous view of the general microstructure in the as-polished condition. It also revealed crystallographic texture, giving more insight into the solidification patterns, grain size, strain contours, and heat flow direction of the weld during cooling (Figs 3-6).

By combining data collected using optical microscopy, SEM-BSE, EDS and EBSD mapping, investigators were better able to characterize these technically challenging metallographic samples. Ultimately, this correlative microscopy provided the investigators with sufficient evidence to conclude that no pre-existing flaws were present in the fuel closure plate-to-injector welds. Analyses performed in parallel by other members of the investigation team systematically eliminated all other plausible branches of a fault tree, ultimately determining the root cause as a leaking fuel valve upstream of the injector [3]. Combined with additional rationale, the flight constraint was lifted.

References
[3] The authors would like to gratefully acknowledge our colleagues D. Cone et al, NASA WSTF, Las Cruces NM.
Metallographic Preparation of Space Shuttle Reaction Control System Thruster Electron Beam Welds for Electron Backscatter Diffraction

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Background

- On June 17, 2010, an Space Shuttle Reaction Control System (RCS) thruster (S/N 10) failed during a firing test at the NASA WSTF
  - Firing test was being conducted to investigate a previous Oxidizer Valve Low Current
  - The event occurred during the 4th pulse fire test that day
- Misfiring event generated a constraint to launch of STS-133
- Non-Destructive analysis of thruster found a number of cracks associated with the fuel closure plate/injector assembly
  - “Blue Crack” – 45° Acoustic Cavity
  - “Red Crack” – Inboard Fracture between Fuel/OX Passages
  - “Yellow Crack” – Ox Tube EB Weld Crack
  - “Green Crack” – Outboard Fuel Closure EB Weld Fracture
- JSC M&P was asked to evaluate portions of the “Green Crack” and “Red Crack”
Misalignment of Flange/Plate

Injector Cut-Away View

Image source: Orbiter RCS Thruster WSTF Test Stand Failure Investigation
Fracture Map with Clocking Scheme

‘45 Degree’ Acoustic Cavity Cracks
(60 -180˚ CW)

Inboard Fracture between Fuel/OX Passages
(0 - 360˚)

Ox Tube EB Weld Crack
(45 – 160˚ CW)

Outboard Fuel Closure EB Weld Fracture
(300 - 160˚ CW)

EDM Cut Paths

Photo and drawing courtesy of Darren Cone, WSTF
SN_10_-_Red_Crack_(WSTF_M&P_Data)_08-24.pptx
SN 10 RCS Thruster Cross-Section

Fuel Closure Plate (Titanium 6Al-4V)

Injector (C-103 Niobium)

Combustion Chamber

Outboard Fuel Closure To Injector Weld Fracture
SN 10 As Cut (1st) Photography

180° Side
As Abrasive Cut

340° Side

180° Side
As Abrasive Cut

340° Side
SN 10 2nd Cut Photography

165° Side

Metallography Specimen

Metallography Specimen

180° Side

Bending Specimen

160° Side
SN 10 OB Fuel Closure Weld
Metallography

DIC Optical

Cosmetic Weld

BSE SEM

EB Weld Root

Ti 6-4  C-103
SN 10 OB Fuel Closure Weld
Optical Micrographs

Kroll’s Etchant
5 sec swab
SN 10 OB Fuel Closure Weld
SEM Micrographs (165°)
SN 10 OB Fuel Closure Weld
Optical Micrographs (165°)
SN 10 OB Fuel Closure Weld
SEM Micrographs (165°)
SN 10 OB Fuel Closure Weld
Optical Micrographs (165°)
SN 10 OB Fuel Closure Weld
EBSD Inverse Pole Figure Map
Electron BackScatter Diffraction (EBSD) Band Contrast Map (Pattern Quality)

Scanning Electron Micrograph
Gray scale indicates atomic contrast

EBSD Band Contrast Map
Reveals pattern quality and grain boundaries
EBSD Inverse Pole Figure

Scanning Electron Micrograph
Gray scale indicates atomic contrast

EBSD Inverse Pole Figure (IPF)
Reveals crystallographic “texture”
Correlative Scanning Electron Micrographs
Outboard Fuel Closure Welds

S/N 10

S/N 120

S/N 132

S/N 172

Ti    Nb
    Nb    Ti
    Nb    Ti
    Ti    Nb

All montage micrographs set to relative scale
“Green Crack” Conclusions

• No anomalous material condition associated with weld insufficiency was observed in the material surrounding the “Green Crack”
  – No pre-existing flaws were found in the fuel closure plate-to-injector welds of any of the four thrusters evaluated (SN 10, 120, 132, 172)
  – Adequate fusion took place during original EB welding process
  – Microstructure and microhardness (both of the parent materials and fuel closure plate) are consistent with specifications/expectations

• No evidence of fatigue, intergranular cracking (ICG) or other sub-critical mechanisms found
JSC/WSTF M&P Conclusions

- Each of the four primary fractures within the injector (Red, Green, Blue, Yellow) was the result of a single event.
- High heat in conjunction with an oxidizing environment during the fracture ‘event’ resulted in the formation of a titanium-rich molten oxide that was deposited in a “recast” form on the Green and Blue Crack fracture surfaces.
- No evidence was found to indicate that a sub-critical cracking mechanism contributed to the ‘event’. 
Flight Rationale

Failure Scenario

- Liquid Ox Collection
  - Leaking Ox valve
  - Thruster orientation and gravity field allows puddle formation
  - Sufficient time with leak rate for puddling

- Liquid OX Flows thru injector and boundary layer cooling holes into fuel injector manifold
  - Sufficient puddle depth to go through holes

- Sufficient OX in fuel manifold to produce detonation capable of causing injector damage

- Single firing to produce explosion
Flight Rationale

1. Flight valves less susceptible to leakage than S/N 10.

2. Flight conditions prevent liquid oxidizer intrusion into fuel manifold.

3. Leak detectors and existing Flight Rules make firing a leaking thruster unlikely.
References

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- L1L S/N10 M&P Conclusions, Orbiter M&P PRT, D. Cone et al, NASA WSTF, Las Cruces NM. 09/15/2010
- RCS Development Thruster S/N 10 Failure Investigation Summary, ORB-BU-3, 10/25/2010
- Orbiter RCS Thruster WSTF Test Stand Failure Investigation, NESC Out-Briefing, Bud Castner & Jeremy Jacobs, 11/02/2010
SN 10 2\textsuperscript{nd} Cut Photography

Diamond Saw Cut

180° Side
165° Side
160° Side
340° Side

165° Side
EDS Dot Map

Electron Image 1
Ti Ka1
Al Ka1
V Ka1
Hf La1
Nb La1
SEM Micrographs
EDS Dot Map

Electron Image 1

Nb Ka1

Ti Ka1

Hf La1

V Ka1

Al Ka1
SN 10 OB Fuel Closure Weld
EDS of Niobium/Weld Interface (165°)
SN 10 OB Fuel Closure Weld
EDS of Niobium/Weld Interface (165°)
SN 10 OB Fuel Closure Weld
EDS of Niobium/Weld Interface (165°)
SN 10 OB Fuel Closure Weld
EDS of Niobium/Weld Interface (165°)
Montages not to scale
SN 172 DIC Optical & BSE SEM Montages
S/N: 10 Red Crack Exposed by End Milling
(180° to 340° Side)
Isolated ‘Red Crack’ Region, Fuel Closure-Side
(180-340° Side)
Isolated ‘Red Crack’ Region, Fuel Closure-Side
(180-340° Side)
Scanning Electron Microscopy
Fuel Closure-Side
180-340°
Scanning Electron Microscopy
Red Crack, Fuel Closure Side (180°-340°)
Scanning Electron Microscopy
Red Crack, Fuel Closure Side (180-340°)
Scanning Electron Microscopy
Red Crack, Fuel Closure Side (180-340°)

180° Side  340° Side

S-4800 20.0kV 5.6mm x100 SE(M) 9/7/2010
500um

S-4800 20.0kV 5.6mm x500 SE(M) 9/7/2010
100um
“Red Crack” Summary

• No thumbnails evident
  – No conventional fatigue observed
  – No intergranular cracking observed
  – No unexplained discoloration

• Continuous shear band evident along inboard and outboard welds
  – Shear dimples evident along bands
  – No significant interruptions in shear bands

• Fracture surface across niobium
  – Mostly cleavage-like facets
  – Occasional shear dimples between facets