SOLID STATE WELDING DEVELOPMENT AT MARSHALL SPACE FLIGHT CENTER

R. Jeffrey Ding

NASA-Marshall Space Flight Center
Materials and Processes Laboratory
Welding and Manufacturing Team
Huntsville, AL, USA

May 27, 2011

Robert.j.ding@nasa.gov

AGENDA

- Introduction
- NASA's Marshall Space Flight Center
- Solid State Welding Process Development
  - Thermal Stir Welding (TSW)
  - Ultrasonic Stir Welding (USW)
    - Experimentation leading to the USW prototype system
    - First USW welds
- Conclusions

Robert.j.ding@nasa.gov

INTRODUCTION

- Engineering Directorate (ED01)
  - Materials & Processes Laboratory (EM01)
    - Metals Engineering Division
      - Metal Joining and Process Branch
        - Welding and Manufacturing Team (EM32)

- B.S. Welding Engineering -The Ohio State University
- M.S. Science – University of Tennessee
- 26 years at NASA's MSFC

Robert.j.ding@nasa.gov

WHAT IS TSW AND USW?

TSW

- U.S Patents – 7,980,449 8,127,977 8,225,984
- A solid state weld process consisting of an induction coil heating source, a stir rod, and non-rotating containment plates
- Independent heating, stirring and forging controls
- Decouples the heating, stirring and forging process elements of FSW.

Robert.j.ding@nasa.gov

WHAT IS TSW AND USW?

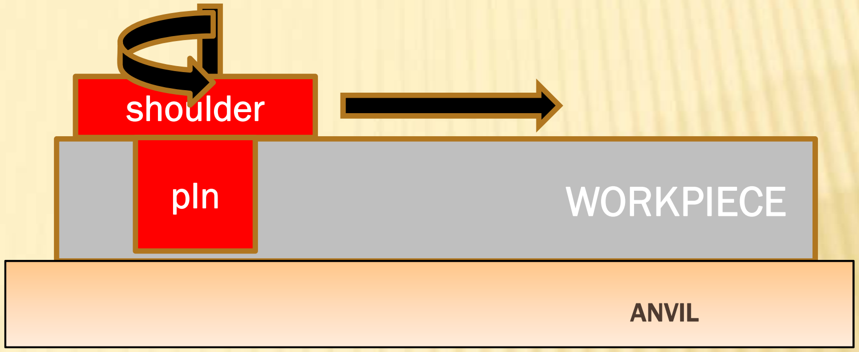
USW

- U.S Patents – 7,568,608
- A solid state weld process consisting of an induction coil heating source, a stir rod, and a non-rotating containment plate
- Ultrasonic energy integrated into non-rotating containment plate and stir rod
- Independent heating, stirring and forging controls
- Decouples the heating, stirring and forging process elements of FSW.

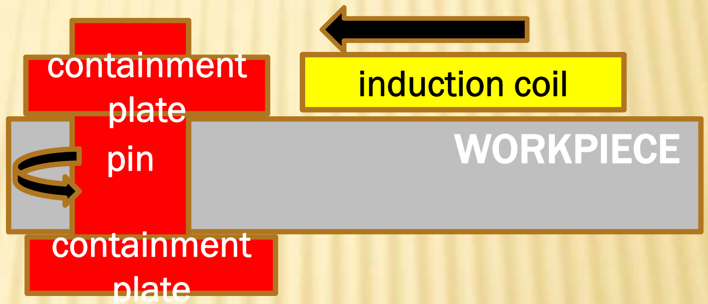
Robert.j.ding@nasa.gov

COMPARISON OF STIR PROCESSES – FSW, TSW, USW

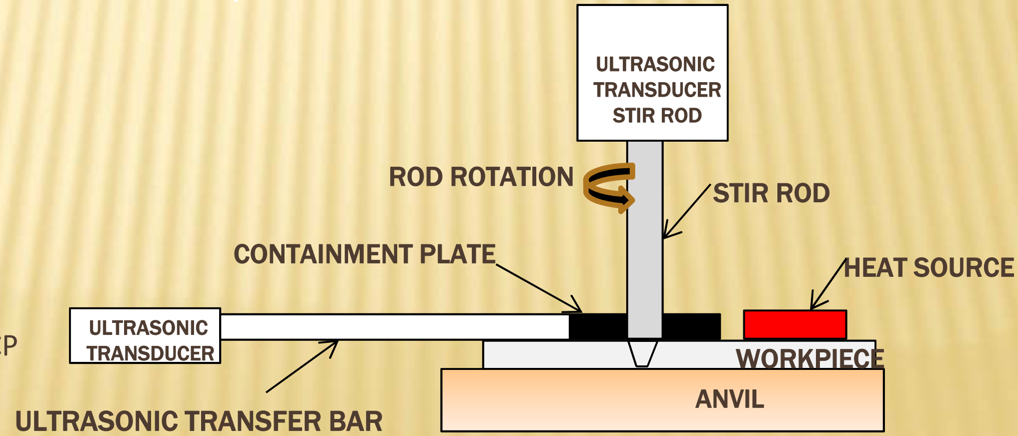
FSW:
Both shoulder and pin rotate together
Material is heated by frictional energy & deformational heating around pin
Cannot decouple heating, stirring, forging



TSW:
Only the pin rotates
Containment plates stationary
Induction coil heats the material
Additional heat is provided by material deformation around the pin
DECOUPLE heating, stirring,forging and Control each independently



USW:
Only the pin rotates
Containment plates stationary
Induction coil heats the material
Additional heat is provided by material deformation around the pin
Ultrasonic energy heats
Ultrasonic energy integrated into stir rod and CP
DECOUPLE heating, stirring,forging and Control each independently



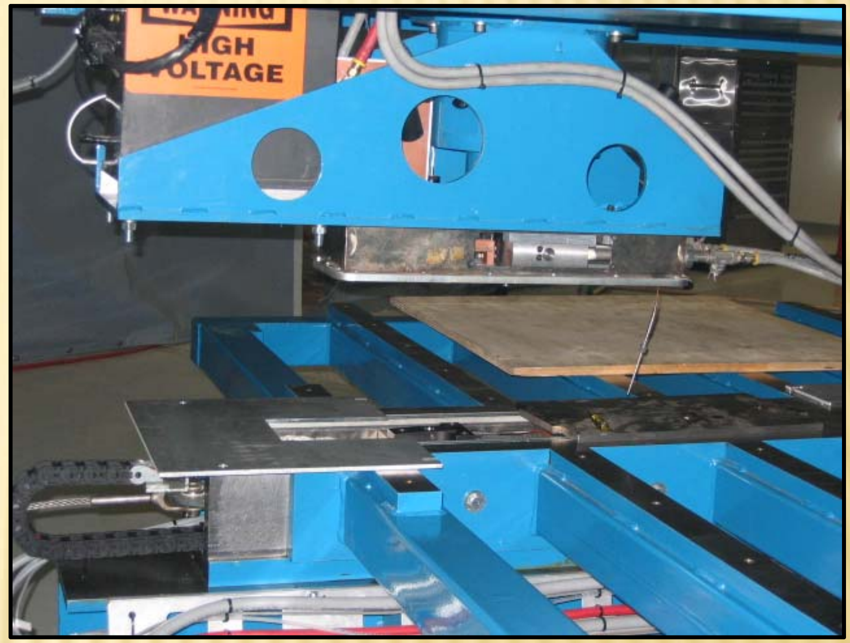
Robert.j.ding@nasa.gov

THERMAL STIR WELDING WILL BE PRESENTED

Robert.j.ding@nasa.gov

THERMAL STIR WELD SYSTEM AT MSFC

Thermal Stir Weld System



Upper and lower shroud and induction coil

Thermal Stir Weld System Capabilities

- Thermal stir welding (TSW)
- Conventional friction stir welding (C-FSW)
- Self-reacting friction stir welding (SR-FSW)
- Hybrid TSW (H-TSW)
- Hybrid FSW (H-FSW)

Robert.j.ding@nasa.gov

RECOGNTION OF TITANIUM TSW SUPPORT AT MSFC

- Solid state joining of alpha and near-alpha titanium alloys conducted at MSFC for Keystone Synergistic Enterprises, Inc. through NASA Space Act Agreement (SAA) process
- In support of Phase I and Phase II Small Business Innovative Research (SBIR) sponsored by Defense Advanced Research Projects Agency (DARPA) and Office of Naval Research (ONR)
- SBIR Phase I and Phase II results are presented

Robert.j.ding@nasa.gov

COMMERCIALLY PURE TITANIUM IS TRADITIONALLY DIFFICULT TO WELD

- Reported Methods

  GTAW, GMAW, laser and more recently hybrid versions of these various processes (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)
- Allotropic phase transformation (~980° C)
- Non-homogenous microstructure that varies as a function of the cooling rate (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)
- Inert gas shielding
- Difficult to maintain adequate inert shielding gases to control the oxidation of the molten pool during fusion welding (Lathabai, et al, 2001, Li, et al., 2009, Leary, et al., 2010)

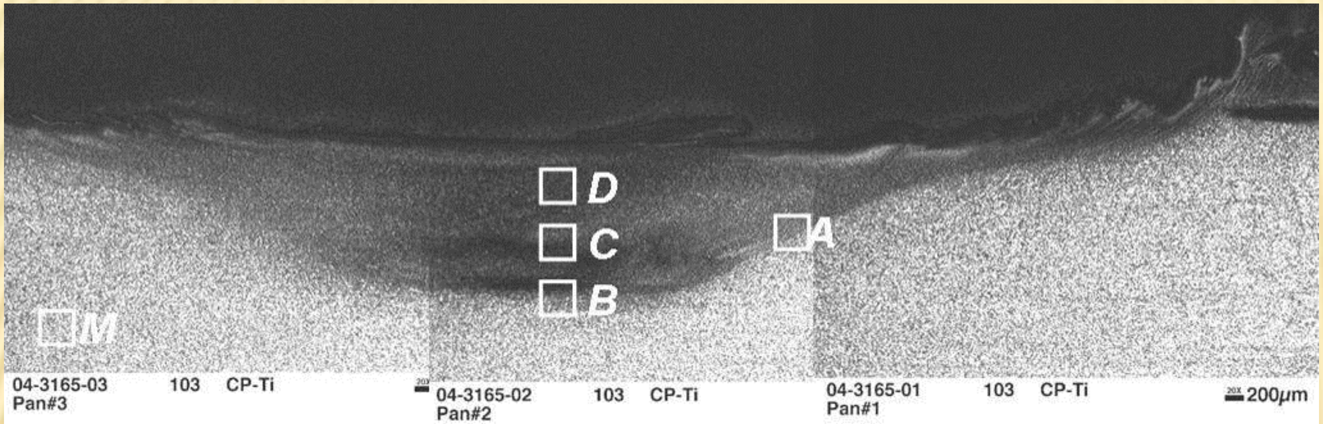
Robert.j.ding@nasa.gov

CONTROL OF FSW TEMPERATURE IS NEEDED TO OBTAIN DESIRED MICROSTRUCTURE

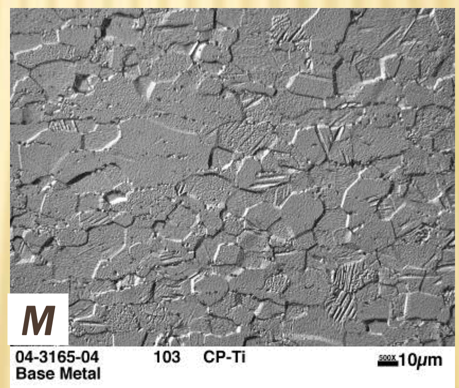
- Cp-Ti can be FSW
  - Lee, et al., 2005- 5.6mm thick plate (panel length not reported)
  - Zhang, et al., 2008- 3mm thick plate (panel length not reported)
- Final microstructure in the stir zone (SZ) depends of temperature during TSW'ing (avoid β-transus)
  - Precise temperature control ensures the a-phase is retained during joining to produce a homogenous microstructure
- Lower temperatures are beneficial to minimize oxidation and distortion

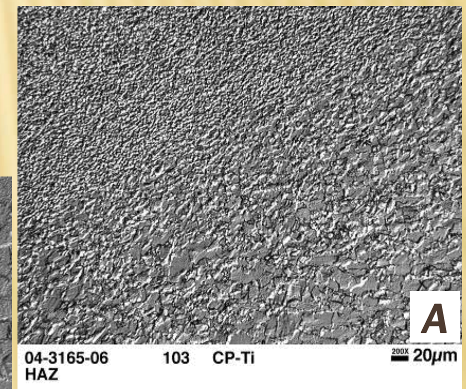
Robert.j.ding@nasa.gov

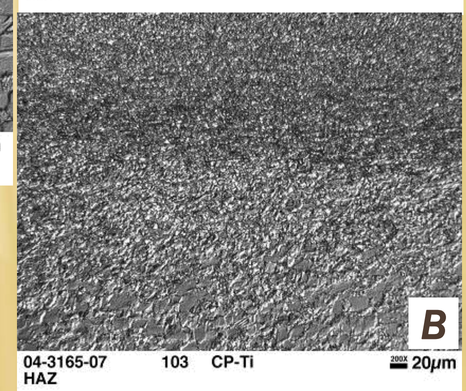
SBIR PHASE I RESULTS



Successful in FSW'ing 3 mm (.250-in) thick 30.5 cm (12-in) long Ti 6-4. Produced acceptable microstructure , however, sharp grain size gradients degraded mechanical properties (ductility and toughness) and pin tool life considered problematic.







SBIR PHASE I RESULTS (cont)

Objective: Demonstrated TSW Process Feasibility

Demonstrated Thermal Stir Joining process is capable of producing 3 mm (.250-in) thick 30.5 cm (12-in) long Ti solid-state welds with in-process controlled microstructure; however, much rework of the heating and mechanical systems on TSW equipment was required

Dynamic, in-process control of μ-structure shown feasible with Thermal Stir Joining

Elimination of sharp grain size gradients

Decoupling heating and metal stirring considered enabling for in-process microstructural process control

Robert.j.ding@nasa.gov

FIRST THERMAL STIR WELD OF Ti 6-4

Ti 6-4 bead on plate.

Robert.j.ding@nasa.gov

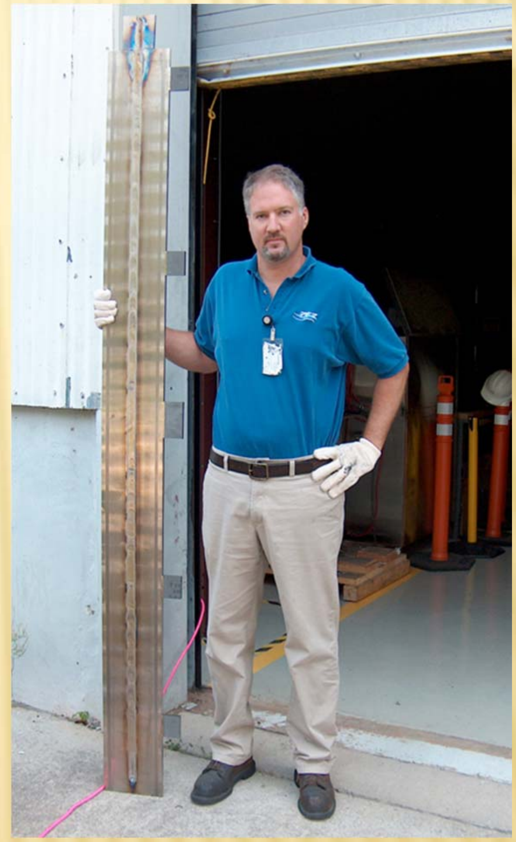
SBIR PHASE II OBJECTIVES AND DELIVERABLES

- Transition to 12.1 mm (.500-in) thick CP Ti Grade 2 using both FSW and TSW processes
  - Deliver 274.32 cm (9 foot) long welds – CP & Ti 6-4 ELI
  - Deliver complex geometry (angular) welds
- FSW'ing completed at Michoud Assembly Facility (MAF), New Orleans, LA.
  - After 41.14 m (135 ft) weld and 25 pin tool design changes – still generating wormholes.
- Keystone abandoned FSW portion of project
- Focused on TSW at MSFC

Robert.j.ding@nasa.gov

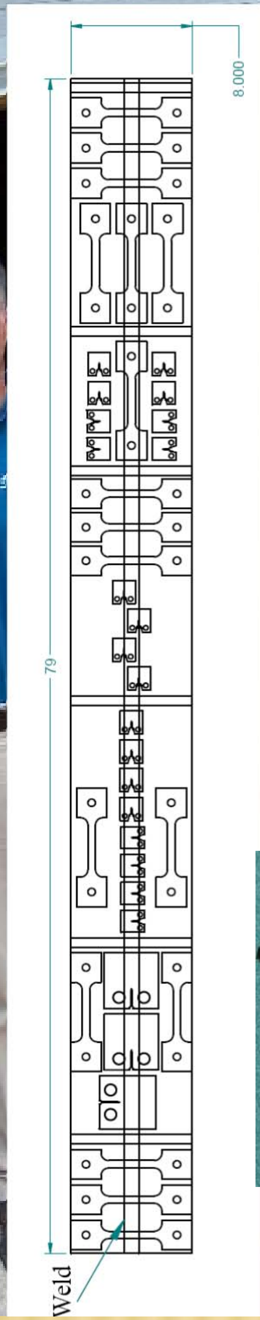
SBIR PHASE II RESULTS

CLOSE UP OF SURFACE FINISH



CHRIS KOLB HOLDING 1ST SUCCESSFUL
8 FOOT LONG CP Ti WELD 12.1 MM THICK

Robert.j.ding@nasa.gov

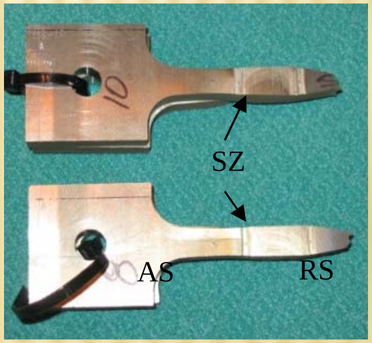


No reduction in strength of TSW'd CP-Ti compared to parent material

	Ref. Prop.*	PM (RD)	RS SZ (Trans.)	SZ (RD)
Yield strength (MPa)	344	333 + 6	353+ 10	371+ 4
Ultimate tensile strength (MPa)	275 to 410	449+ 4	433+ 6	464+ 1

PM-RD

RS SZ-trans



SZ-RD

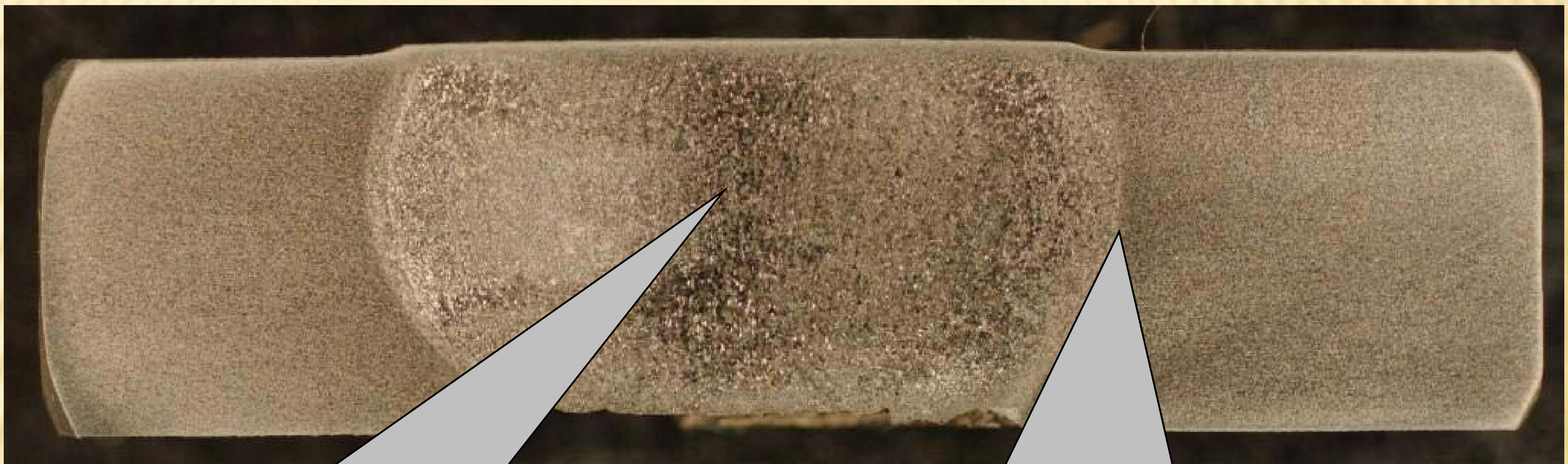
UTS and yield strength increase agrees with results reported in the literature for FSW CP-Ti

Lee, et al., *Mat. Lett.* 2005, Zhang, et al., *Mat. Sci. & Engr.*2008

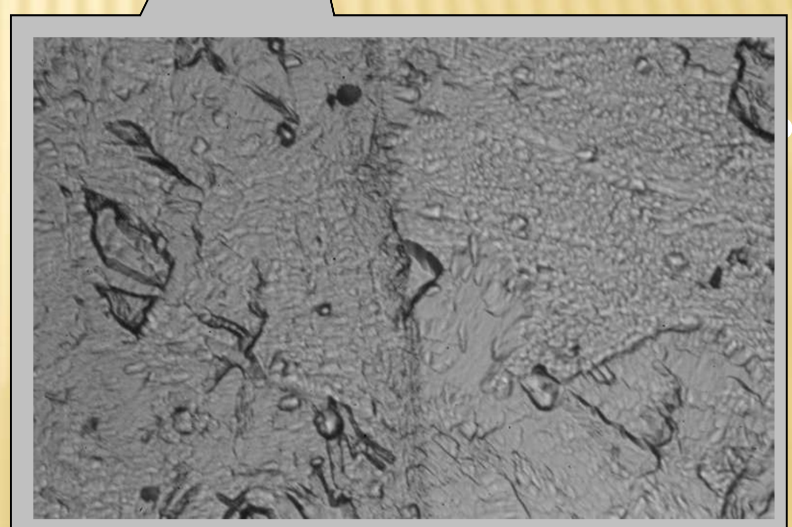
* **www.matweb.com**

Robert.j.ding@nasa.gov

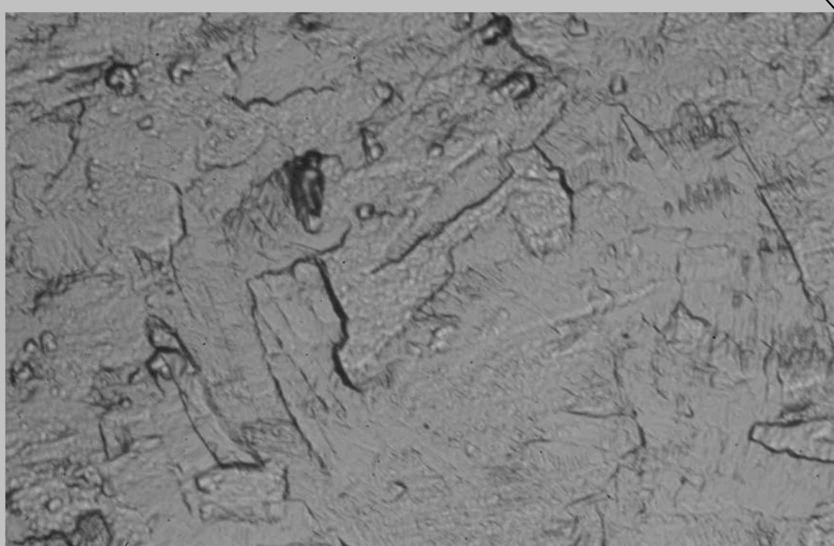
MICROSTRUCTURE CP TITANIUM



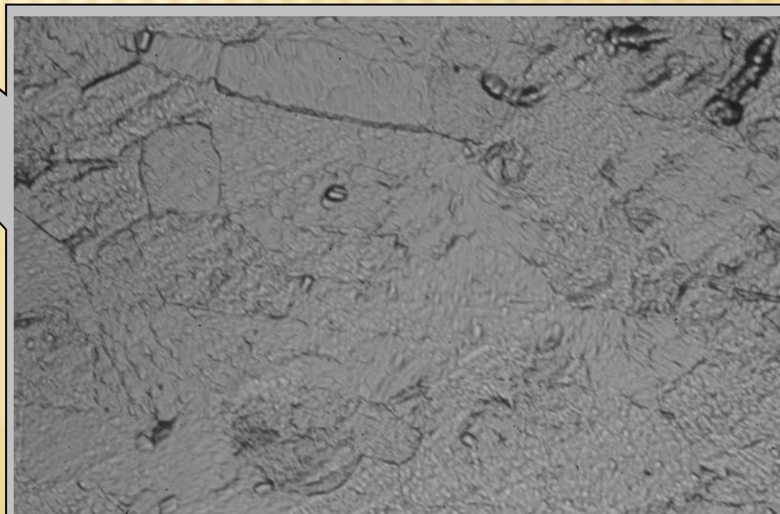
Weld Nugget Center 100x



Advancing Side Fusion Line 100x



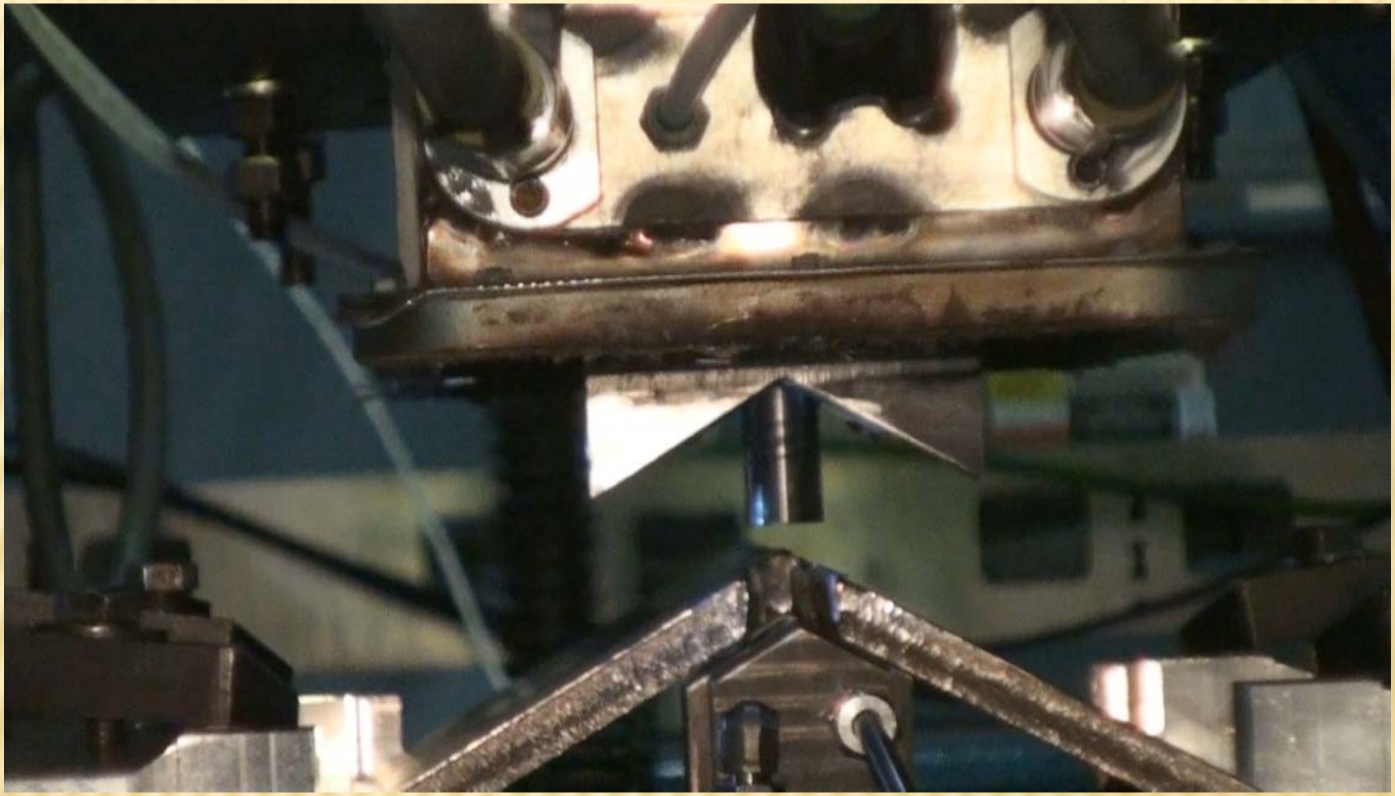
Parent Material 100x



Retreating Side Fusion Line 100x

Robert.j.ding@nasa.gov

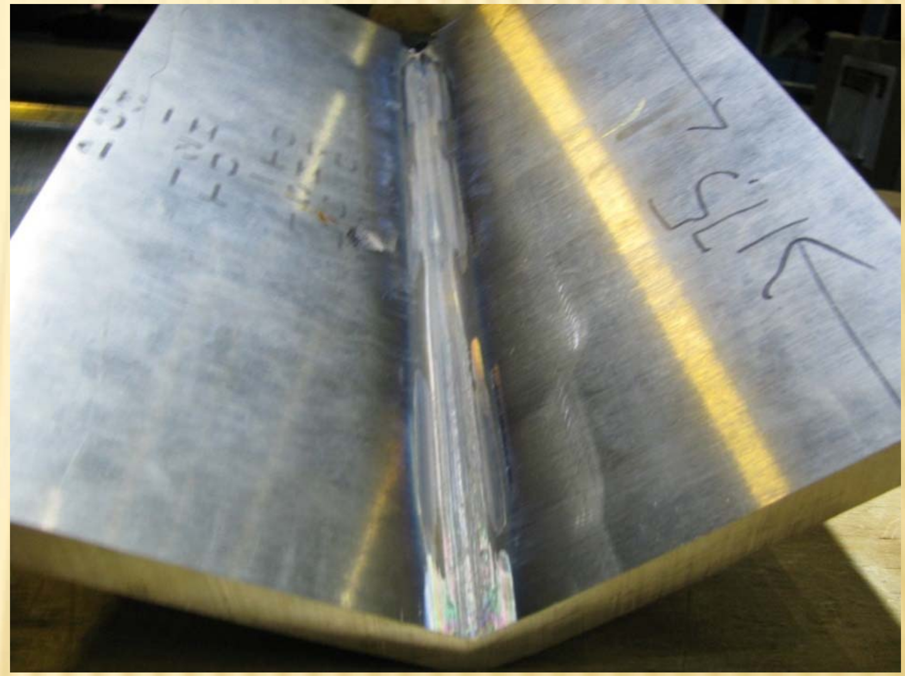
SBIR PHASE II RESULTS (cont.)



Angled weld tooling

Robert.j.ding@nasa.gov

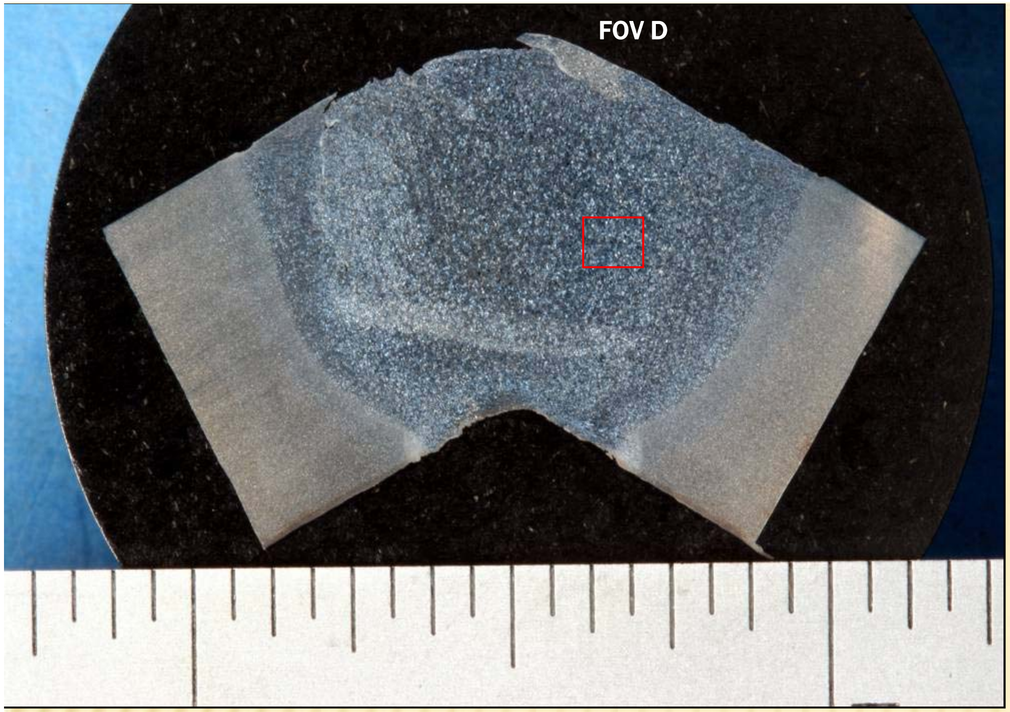
SBIR PHASE II RESULTS (cont.)

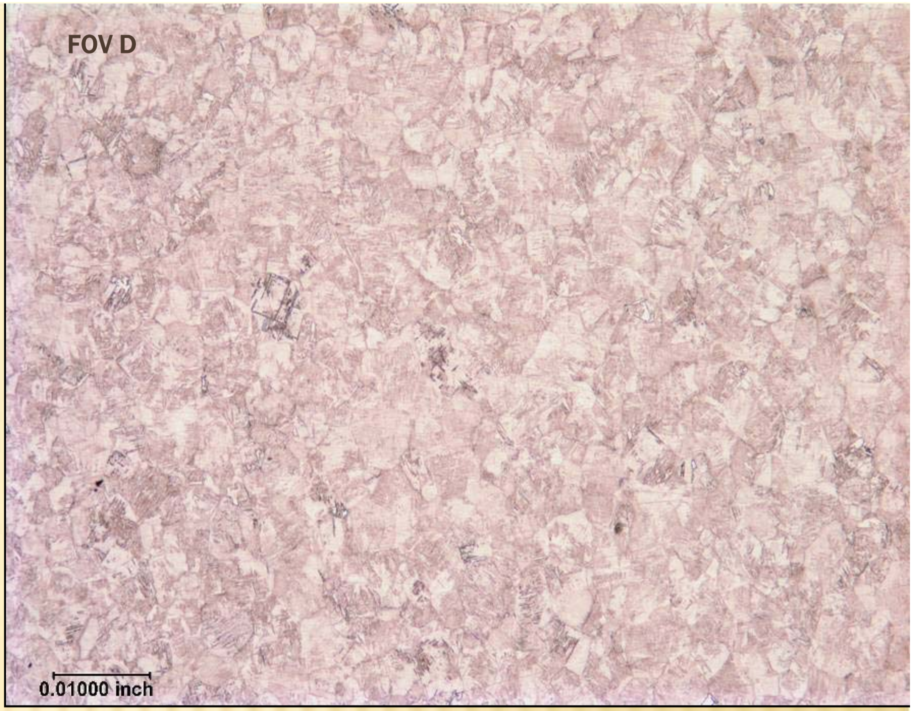


CP Ti .500-in thick angled weld - outside

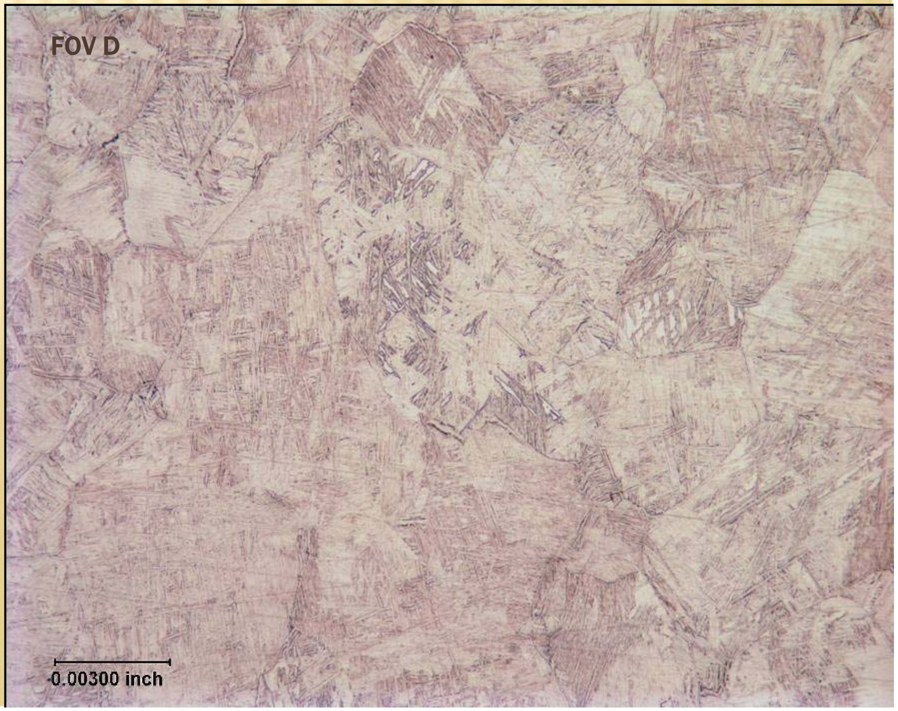
CP Ti .500-in thick angled weld - inside

Robert.j.ding@nasa.gov





Etched Metallurgical Angular Stir Weld Sample (4-22-10 End)



Close-up macro photograph of etched angular Stir weld sample (4-22-10 End) showing approximate field of view for higher mag imagery at right. Note that microphotographs are horizontally inverted.

TOP RIGHT: 50X microphotograph of weld metal region (FOV D).

BOTTOM RIGHT: 200X microphotograph of weld metal region (FOV D).

May 27, 2011

SBIR PHASE II RESULTS (cont.)

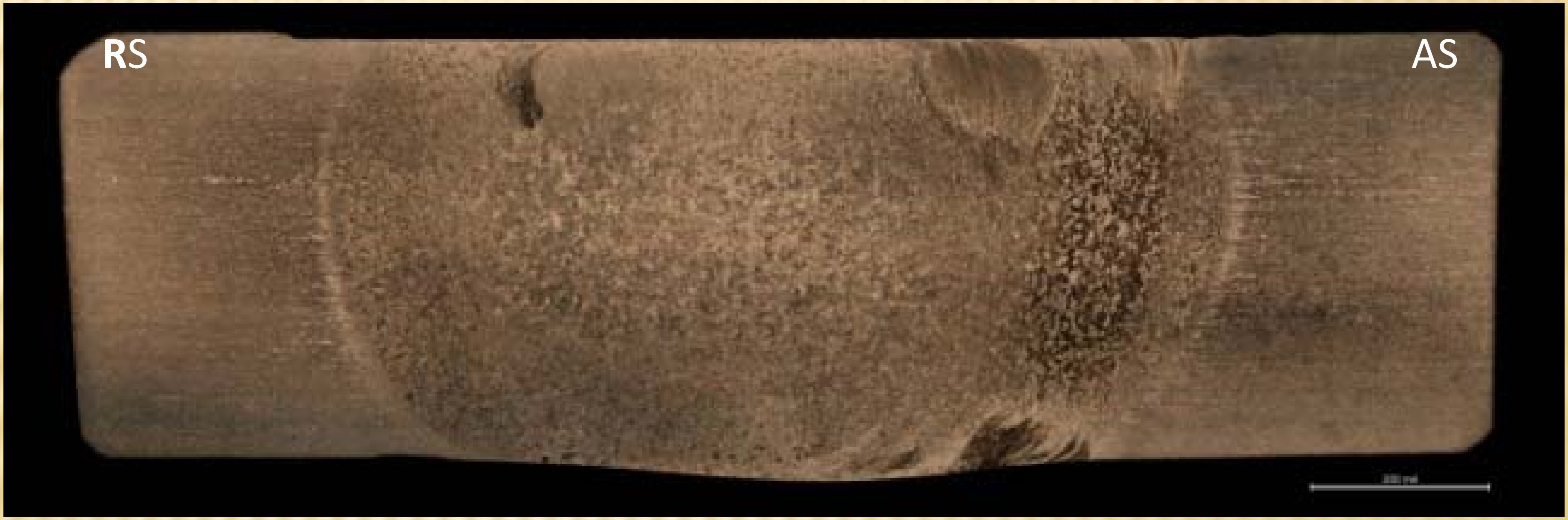
In support of Keystone Synergistic Enterprise's
Small Business Innovation
Research (SBIR) contract N0014-06-C-5200
Sponsored by
Defense advanced Research Projects Agency (DARPA)
and
Office of Naval Research (ONR)

Fabricated from Ti 6Al-4V Extra Low Interstitial alloy

HEXAGON TURET WITH ANGLULAR WELDS

Robert.j.ding@nasa.gov

Defect free cross-sections containing equiaxed grains were obtained



- Minimal HAZ around the weld nugget
- No tool debris in stir zone

Robert.j.ding@nasa.gov

ULTRASONIC STIR WELDING WILL BE PRESENTED

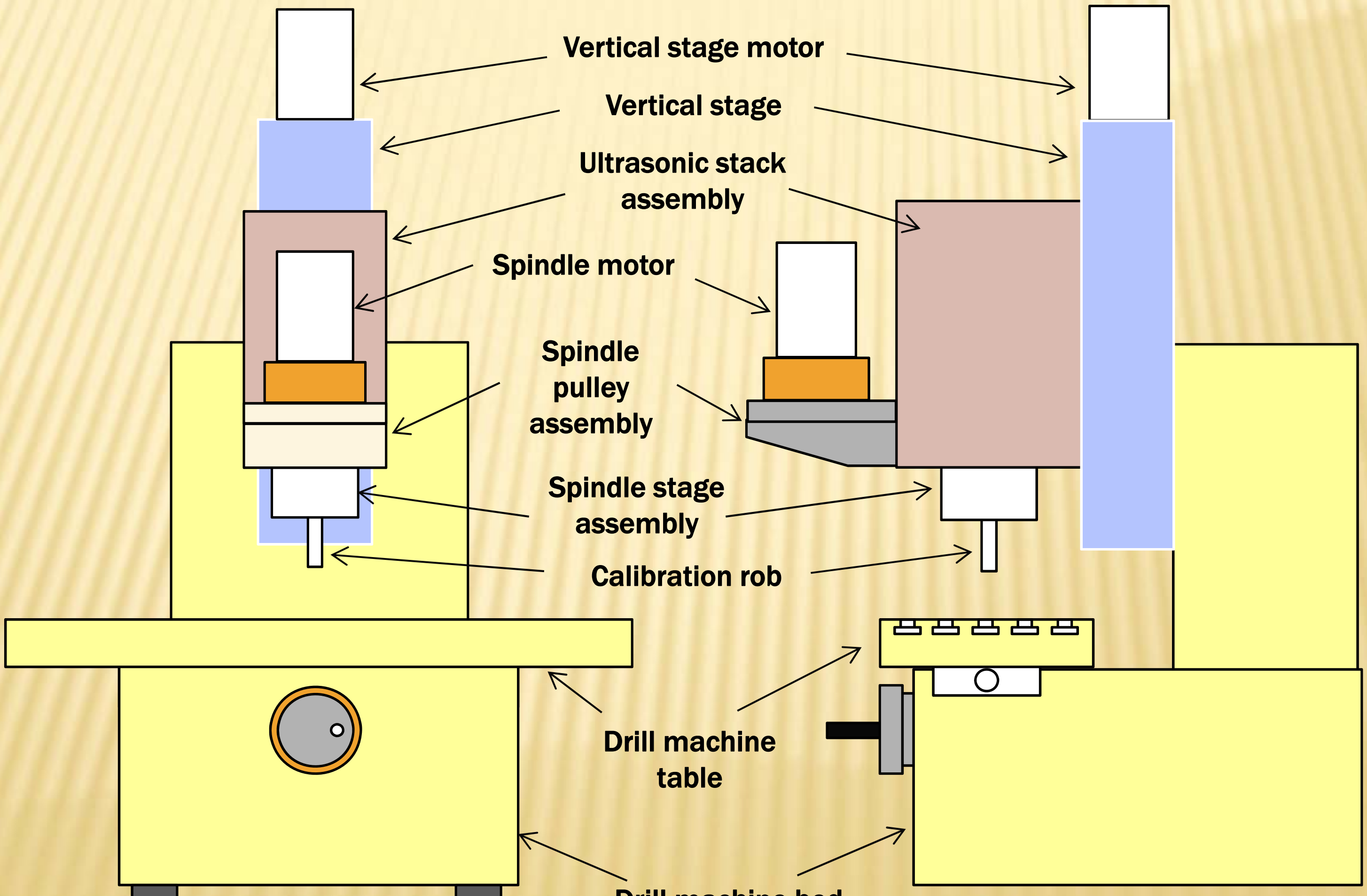
Robert.j.ding@nasa.gov

FIRST HIGH POWER ULTRASONICS (HPU) DATA GENERATED AT MSFC IN 2008

- Leased a Bridgeport machine from Edison Weld Institute (EWI), Columbus , Ohio
  - Integrated with HPU for twist drill applications
  - Used for experimentation
    - Ultrasonic heating
    - Twist drill plunge force reduction
    - Friction reduction between rubbing metallic surfaces

Robert.j.ding@nasa.gov

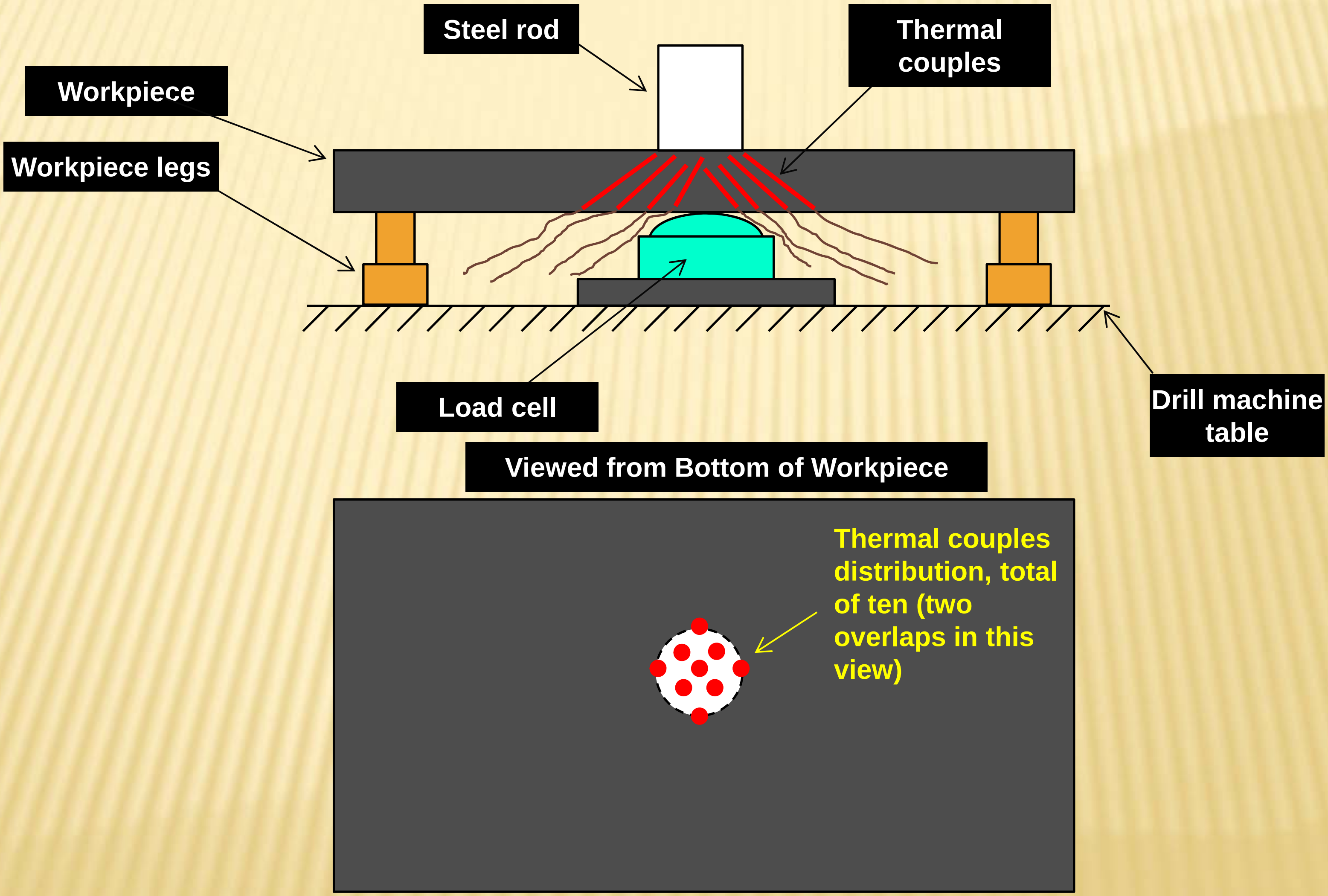
CHARACTERIZATION OF HPU TECHNOLOGY 2008
BRIDGEPORT MACHINE



Robert.j.ding@nasa.gov

Characterization of Thermal Process

Experiment Design



Robert.j.ding@nasa.gov

CHARACTERIZATION OF HPU ASSISTED HEATING

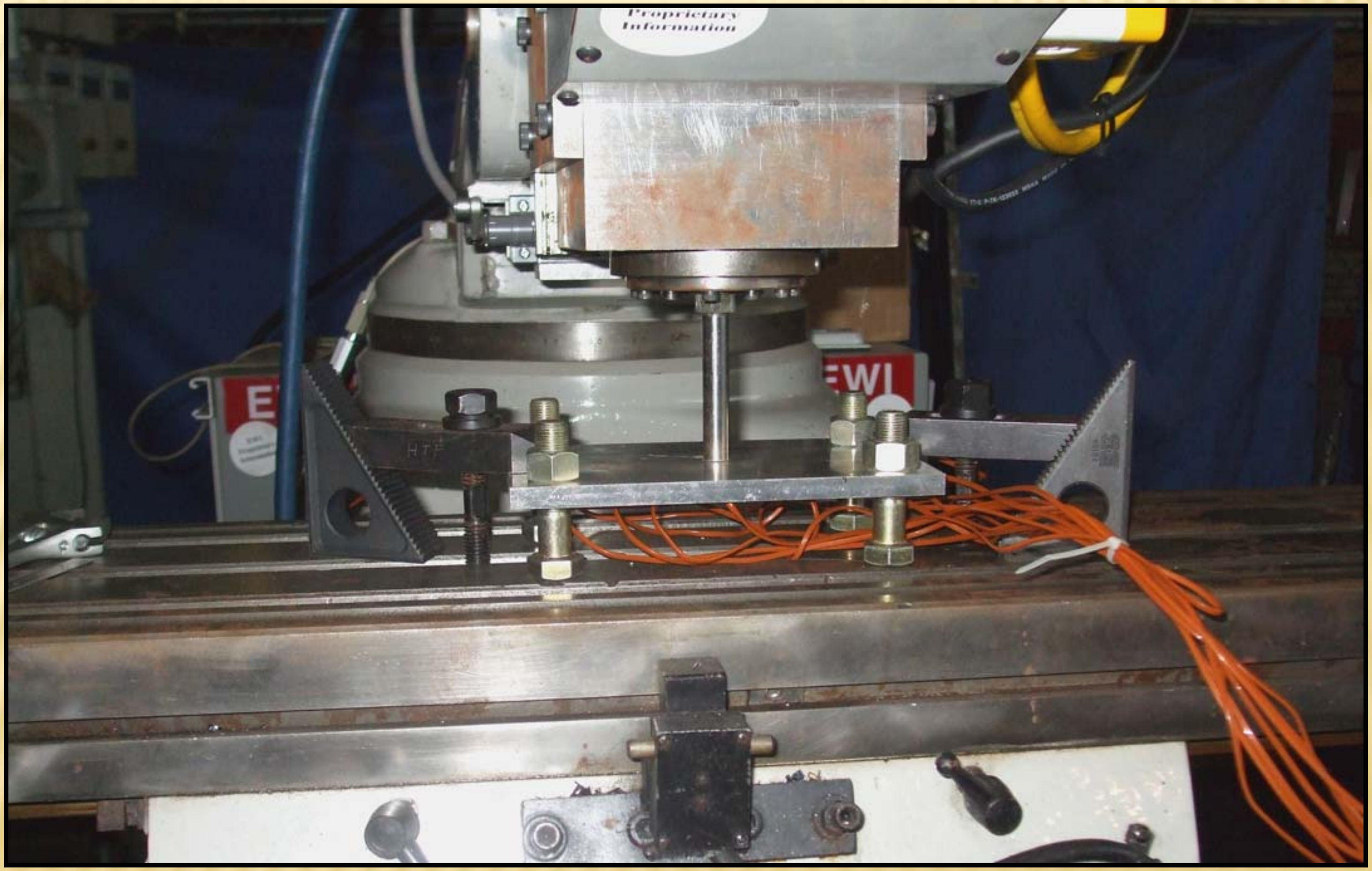
Objective

To investigate the effects of ultrasonic energy on the drilling process (force, torque, temperature, etc.), which will benefit the design of portable tools for remotely-deployable applications.

Robert.j.ding@nasa.gov

CHARACTERIZATION OF HPU TECHNOLOGY

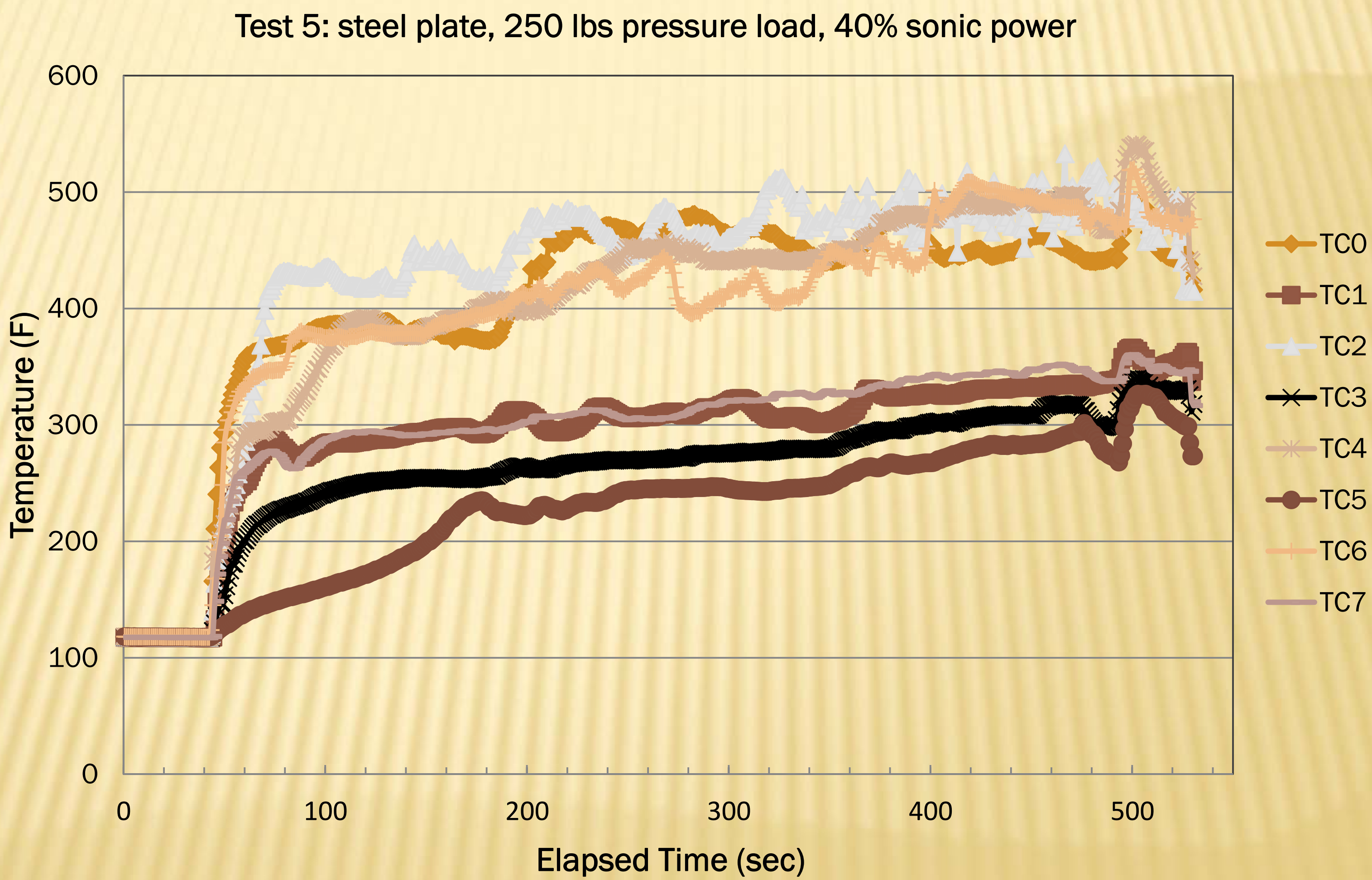
BRIDGEPORT MACHINE – HEATING EXPERIMENT



Robert.j.ding@nasa.gov

Characterization of Thermal Process

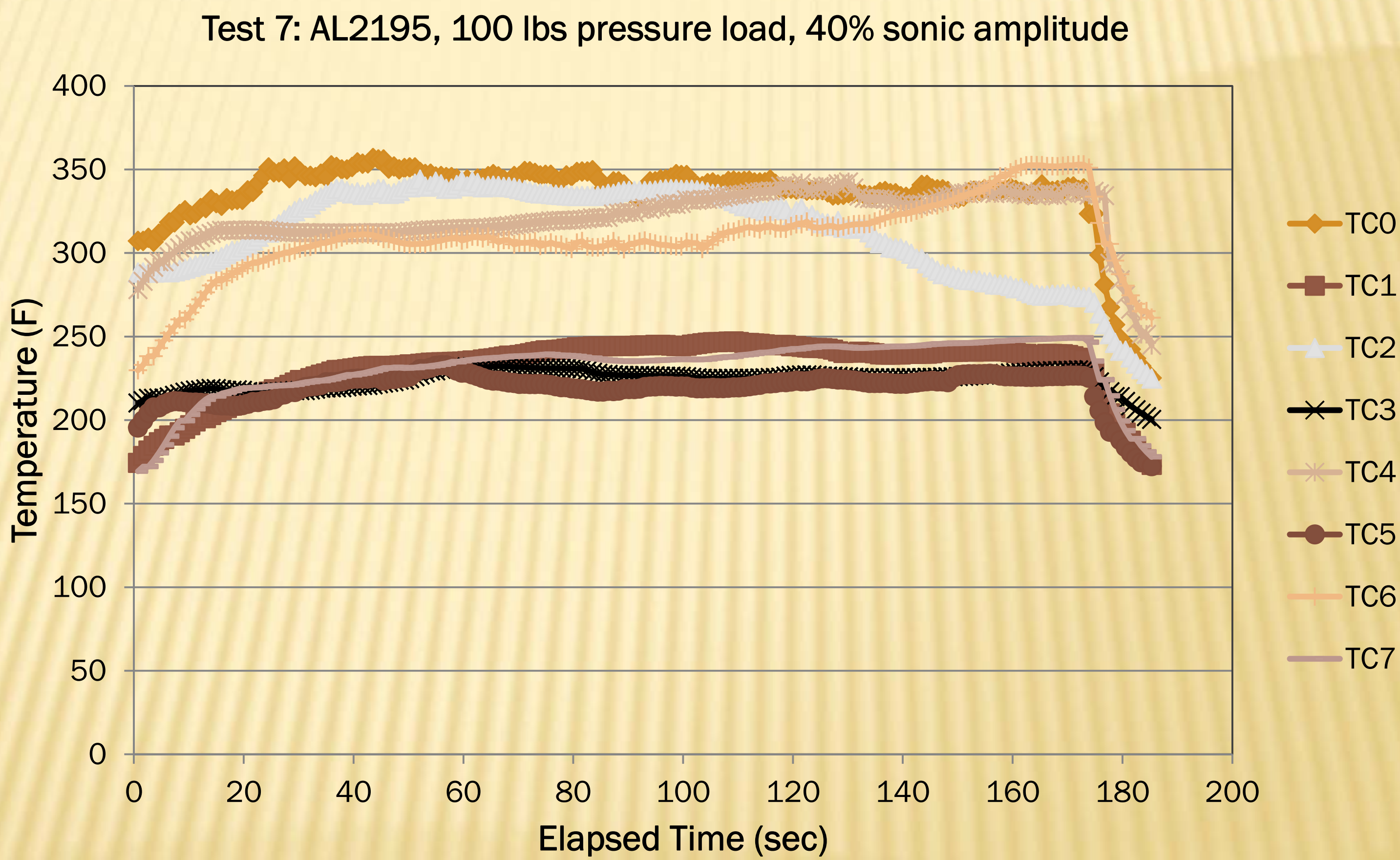
Results



Robert.j.ding@nasa.gov

Characterization of Thermal Process

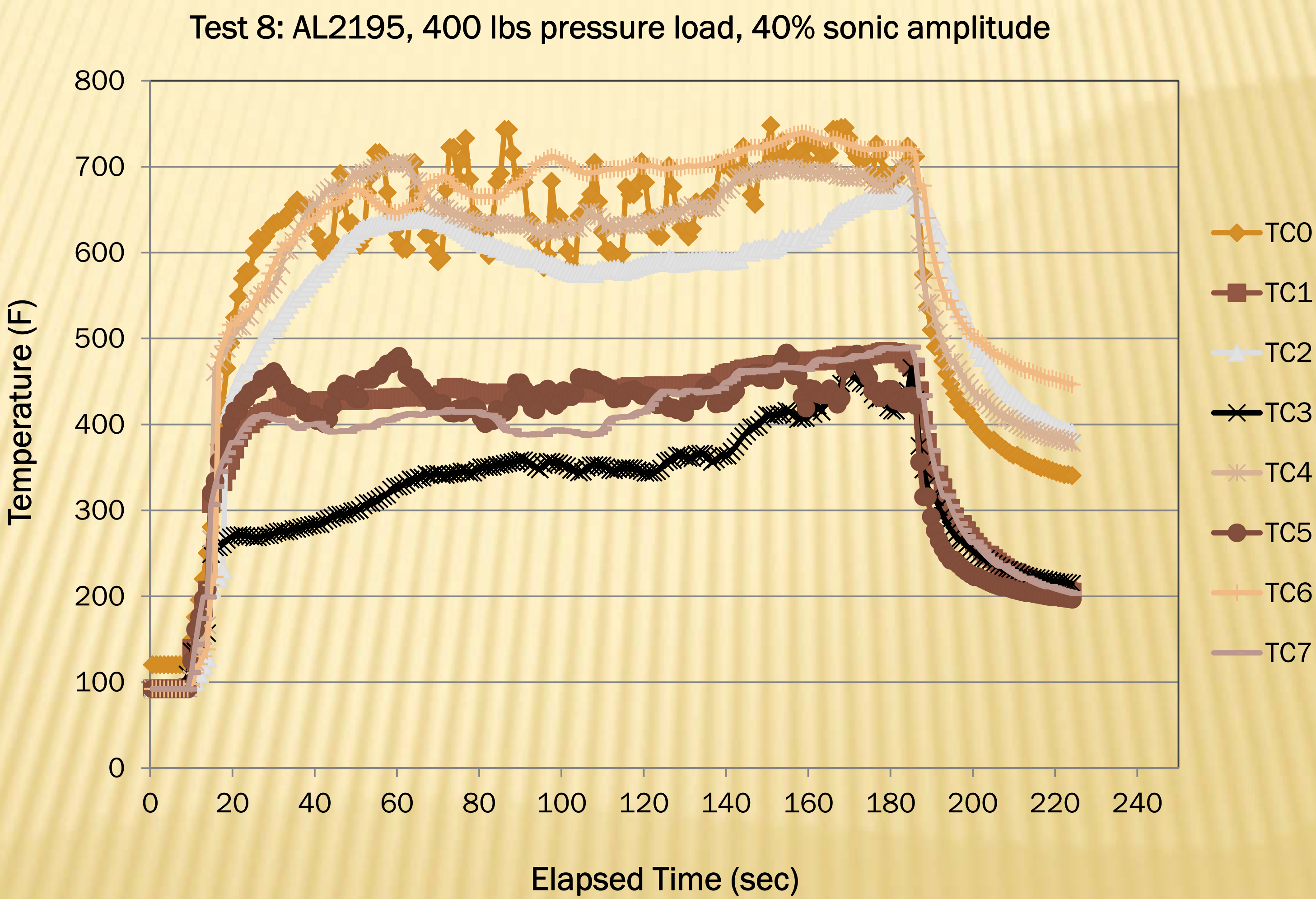
Results



Robert.j.ding@nasa.gov

Characterization of Thermal Process

Results



Robert.j.ding@nasa.gov

CHARACTERIZATION OF HPU ASSISTED DRILLING

Objective

To investigate the effects of ultrasonic energy on the drilling process (force, torque, temperature, etc.), which will benefit the design of portable tools for remotely-deployable applications.

Robert.j.ding@nasa.gov

Characterization of Drilling Process

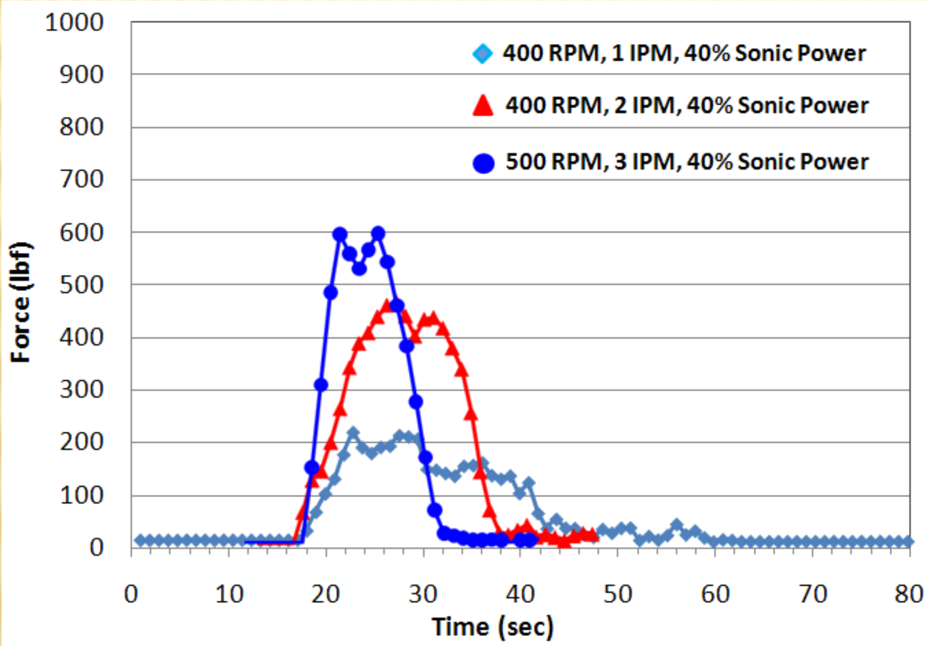
Load Measurement

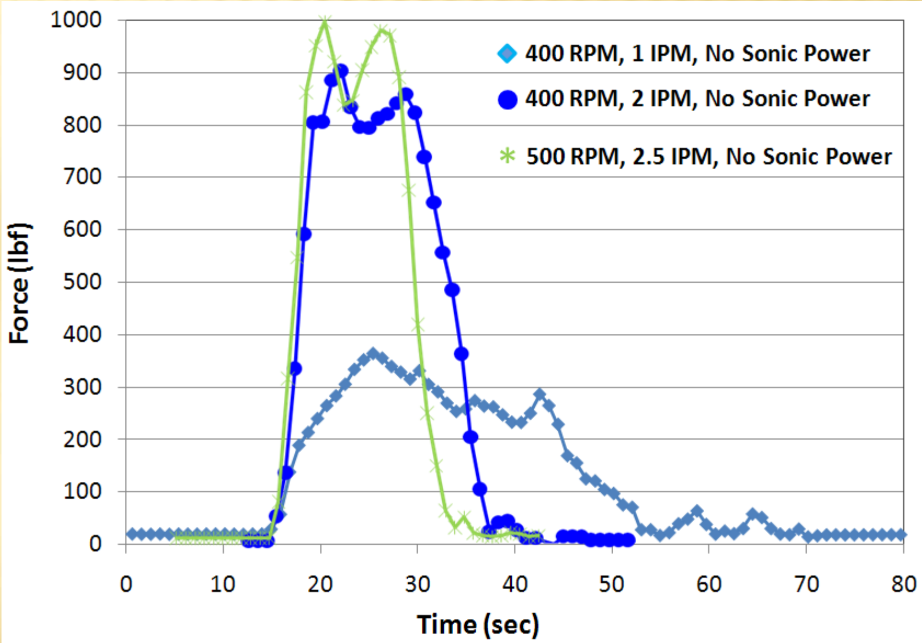
Robert.j.ding@nasa.gov

Characterization of Drilling Process

Results

Sonic-Assisted Drilling vs. Conventional Drilling
(Vertical Drilling Force)





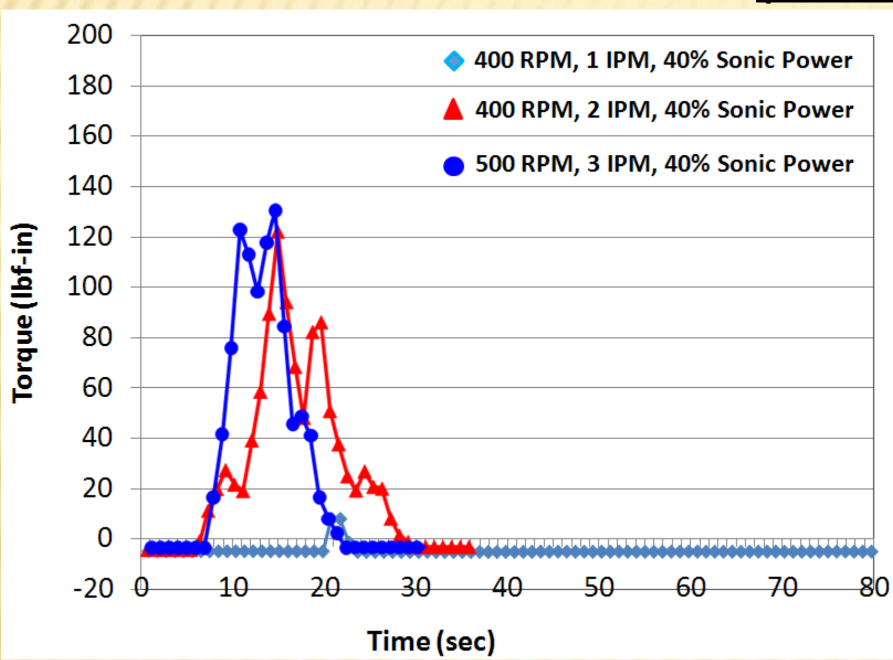
Robert.j.ding@nasa.gov

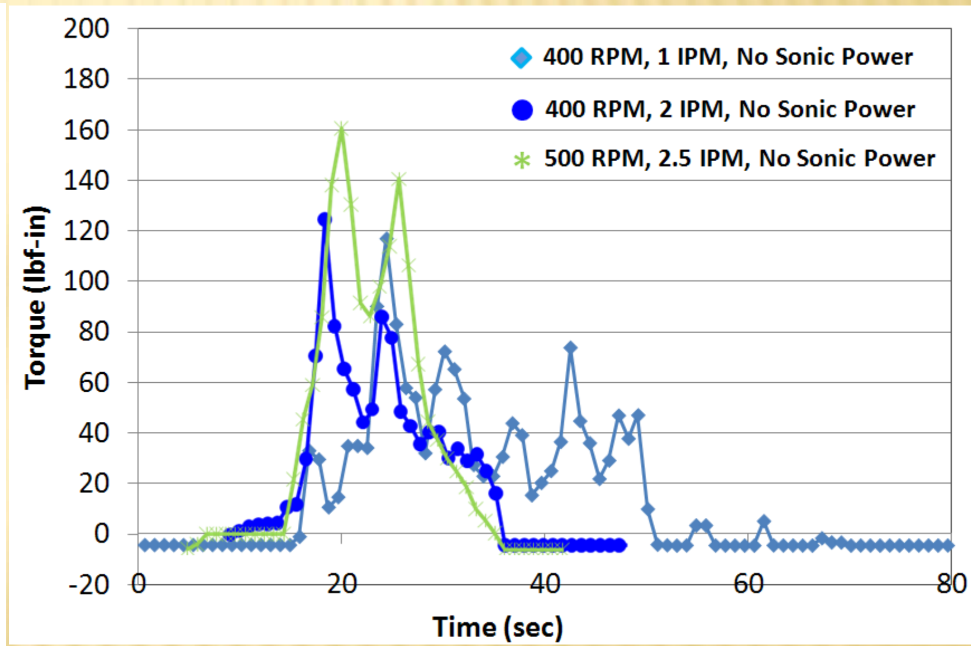
Characterization of Drilling Process

Results

Sonic-Assisted Drilling vs. Conventional Drilling

(Drilling Torque)

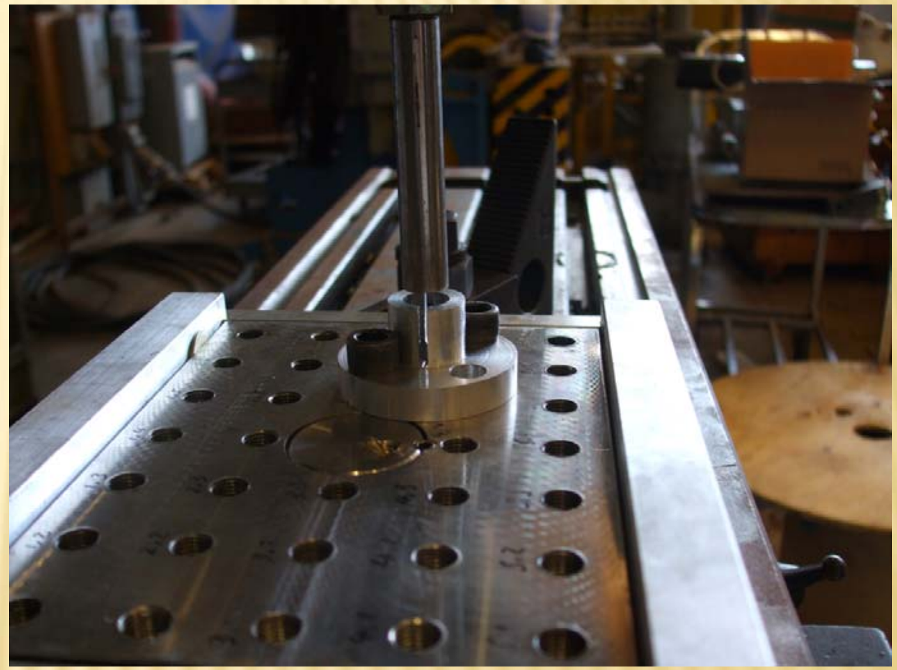




Robert.j.ding@nasa.gov

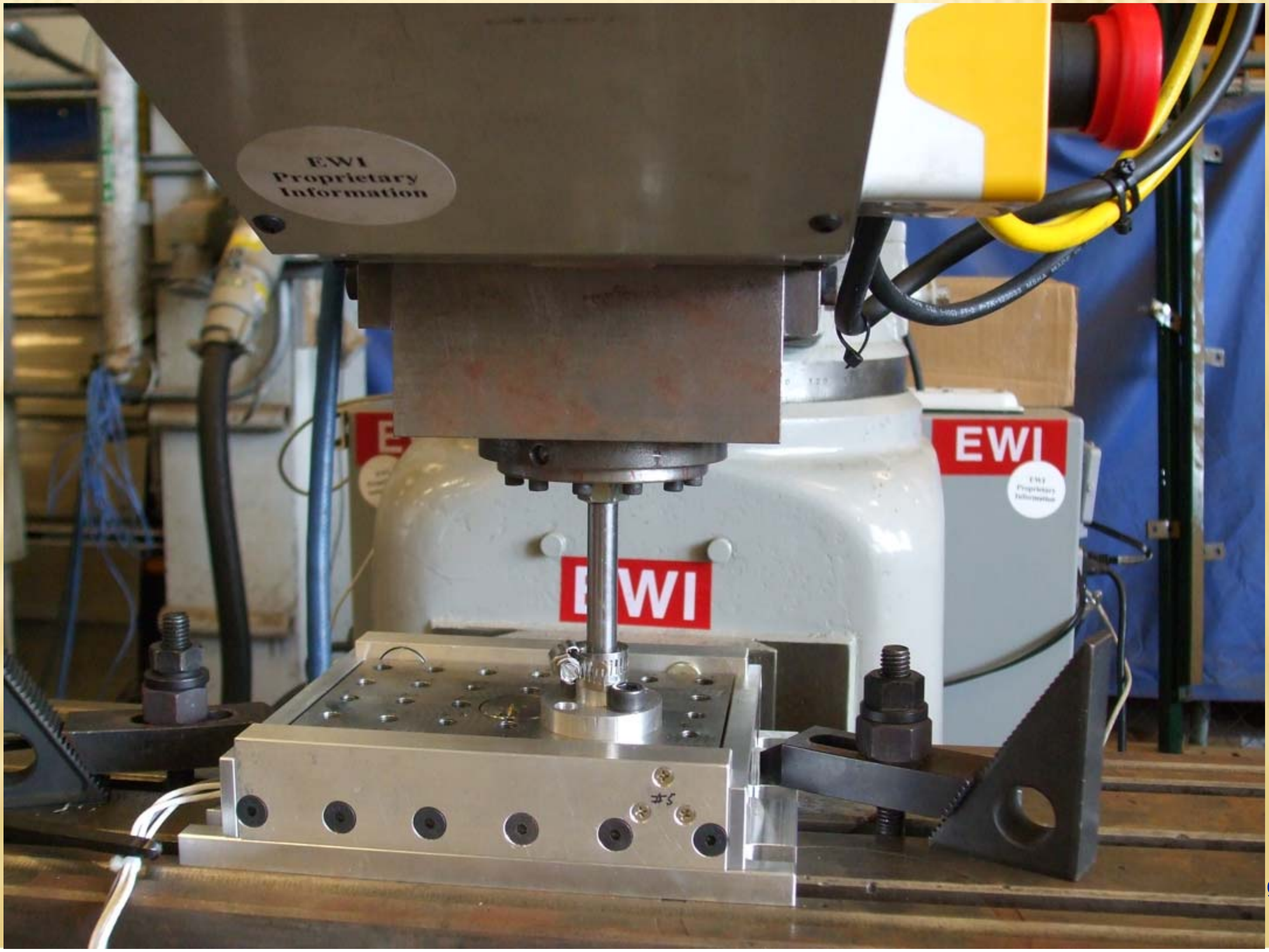
FRICTION REDUCTION SET-UP

FRICTION REDUCTION



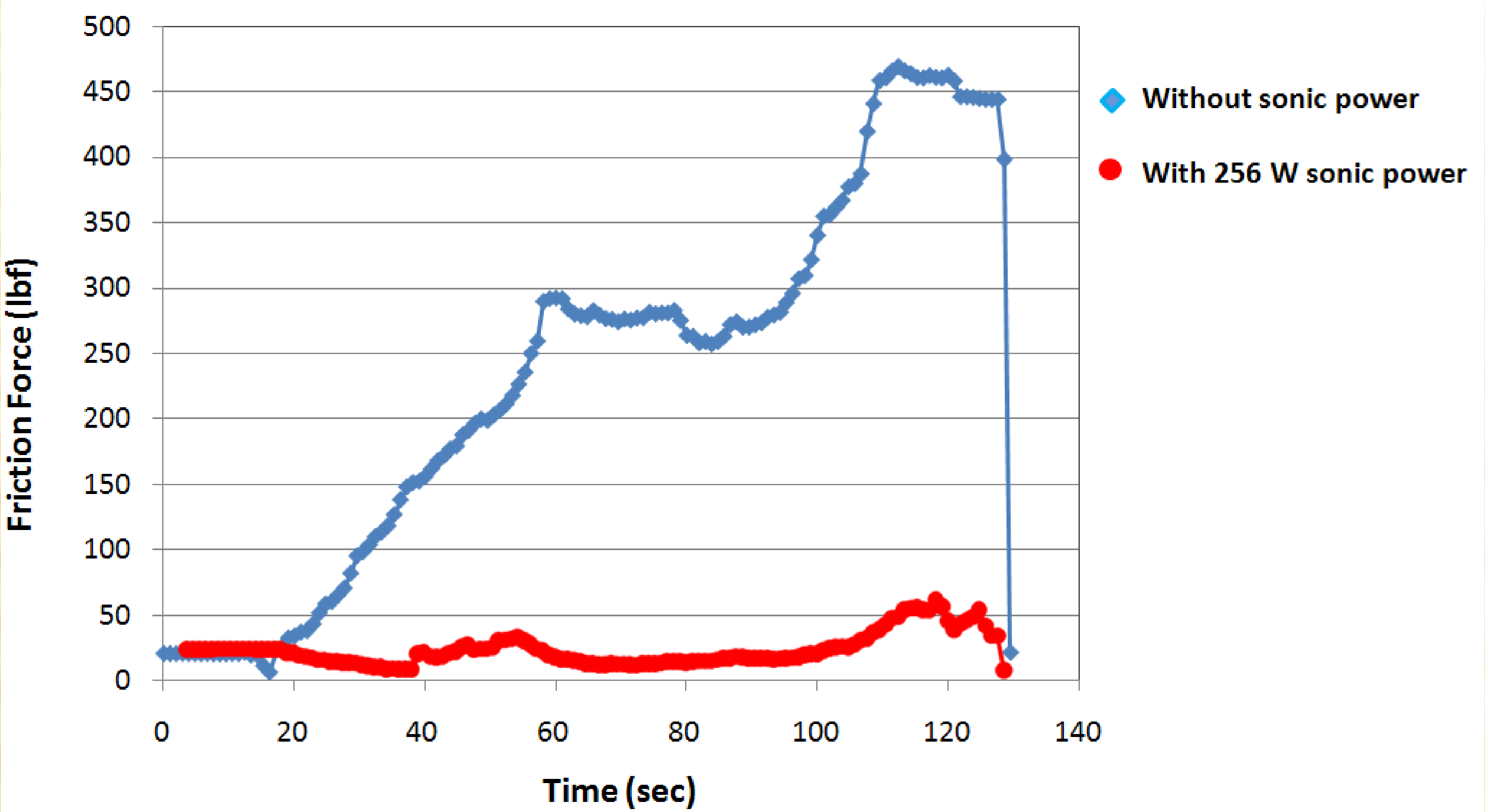
Robert.j.ding@nasa.gov

FRICTION REDUCTION SET-UP



g@nasa.gov

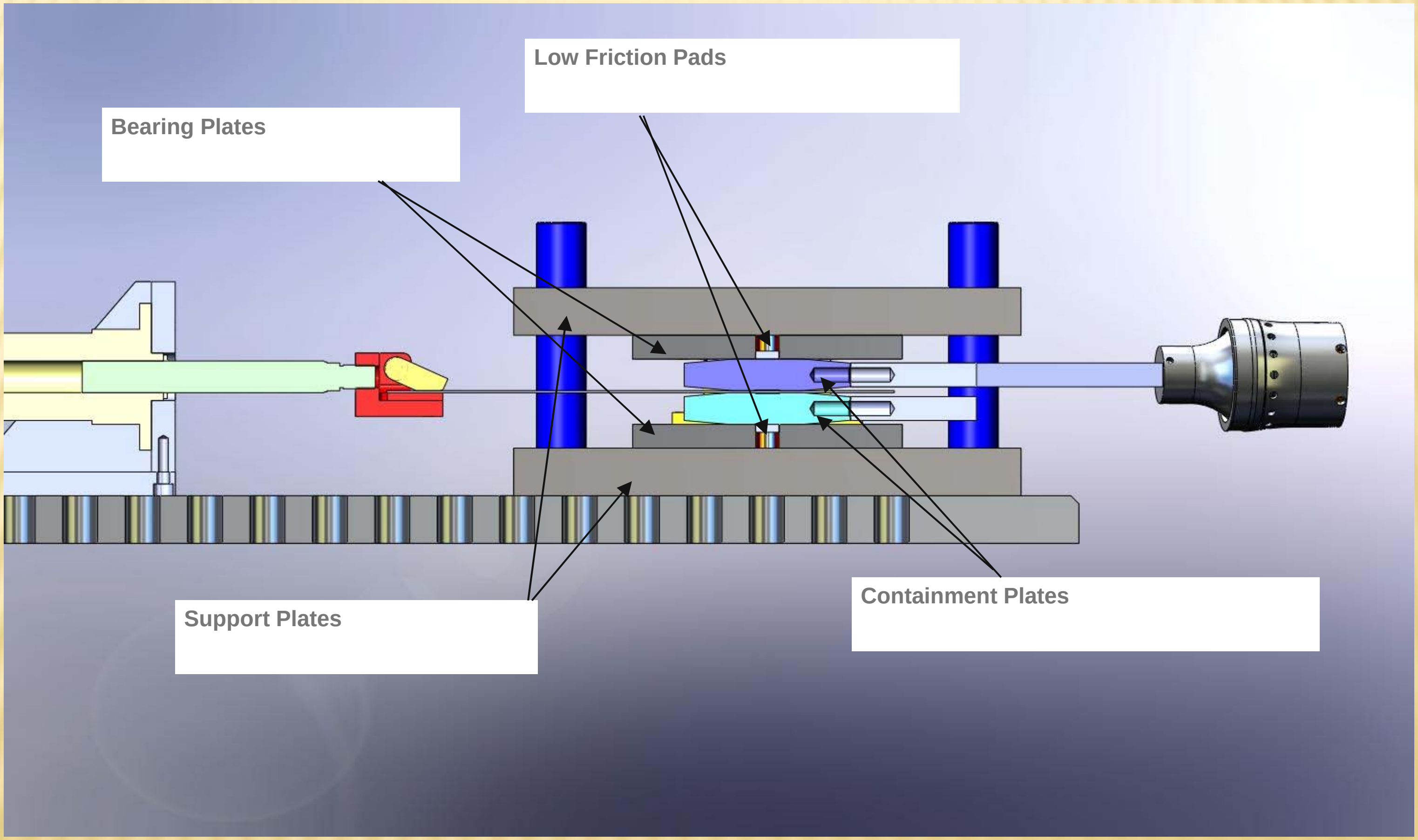
FRICTION REDUCTION RESULTS



May 27, 2011

Robert.j.ding@nasa.gov

SIDE VIEW OF ULTRASONIC FRICTION REDUCTION TEST BED

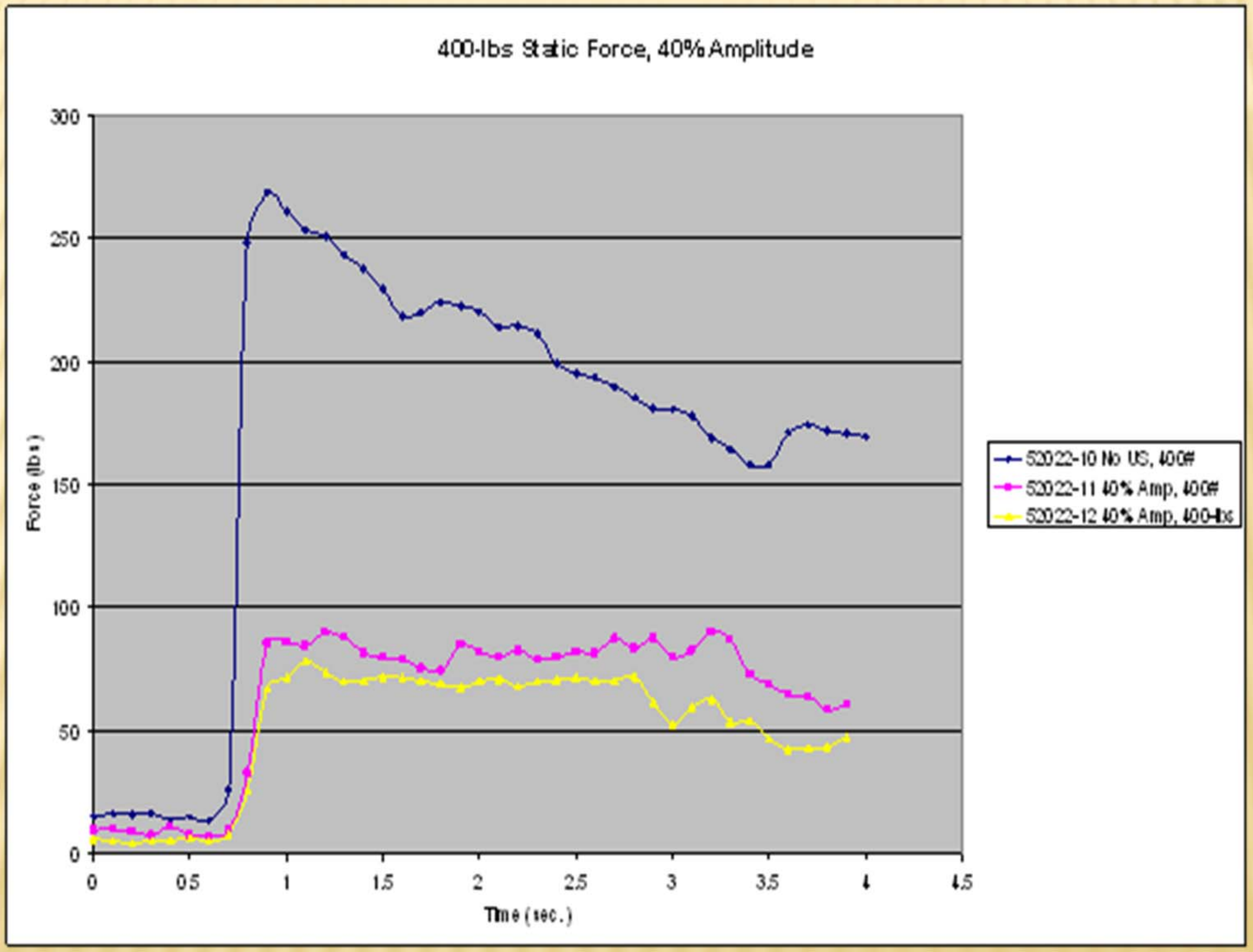


Robert.j.ding@nasa.gov

ULTRASONIC FRICTION REDUCTION TEST BED SET UP

Robert.j.ding@nasa.gov

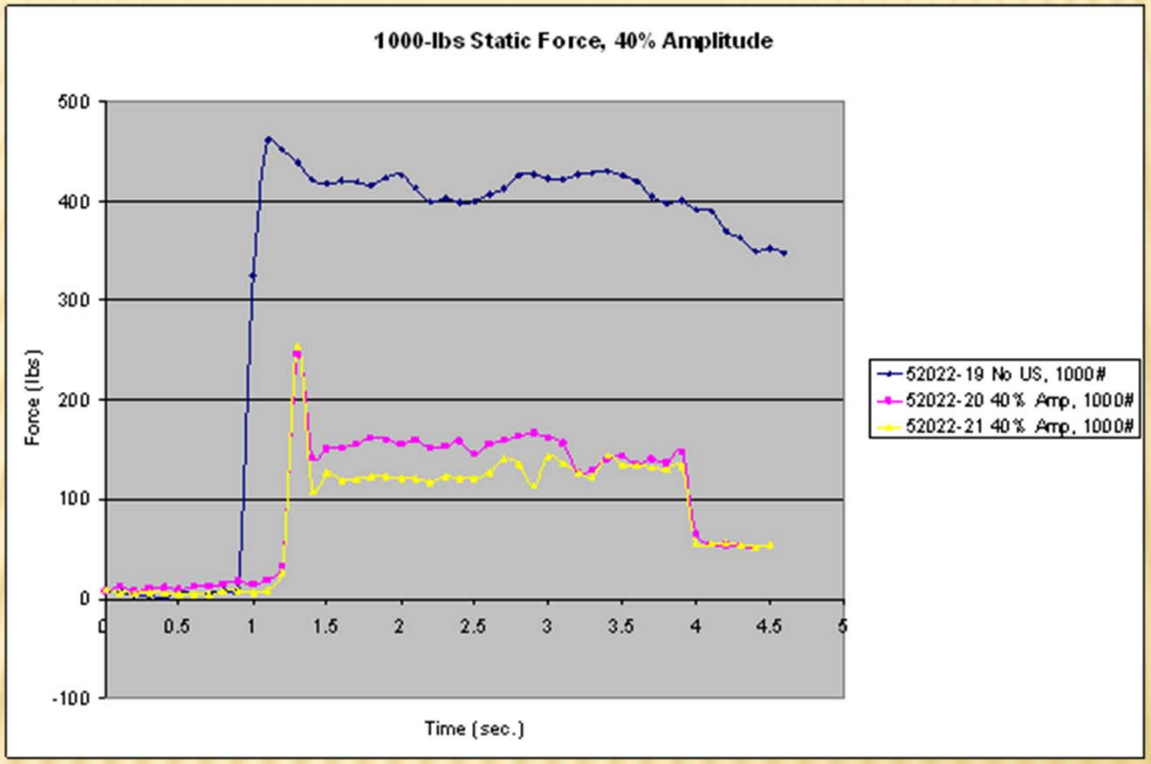
ULTRASONIC FRICTION REDUCTION RESULTS



Clamping – 400-lbs., 40% amplitude

Robert.j.ding@nasa.gov

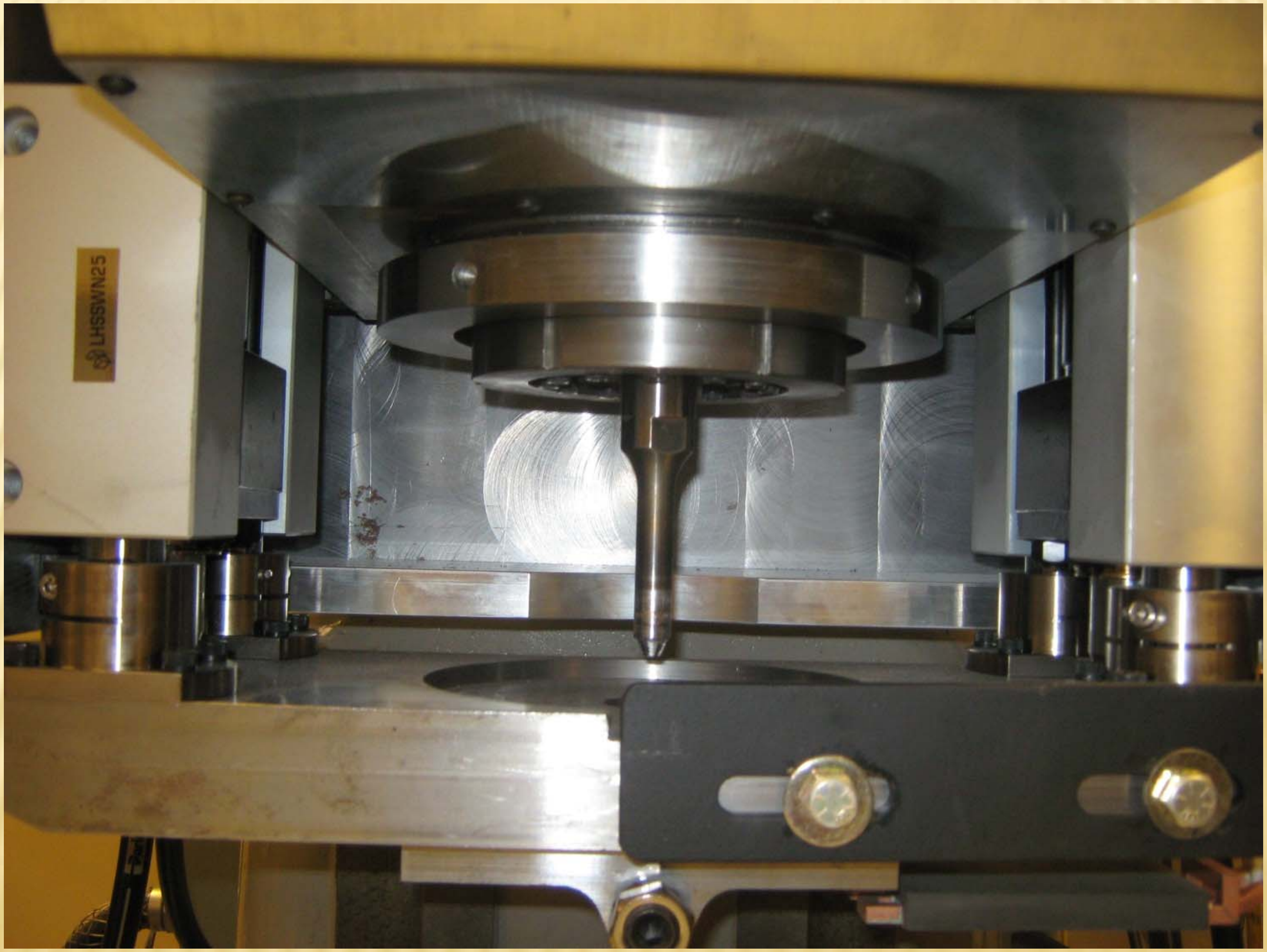
ULTRASONIC FRICTION REDUCTION RESULTS



Clamping – 1,000-lbs., 40% amplitude

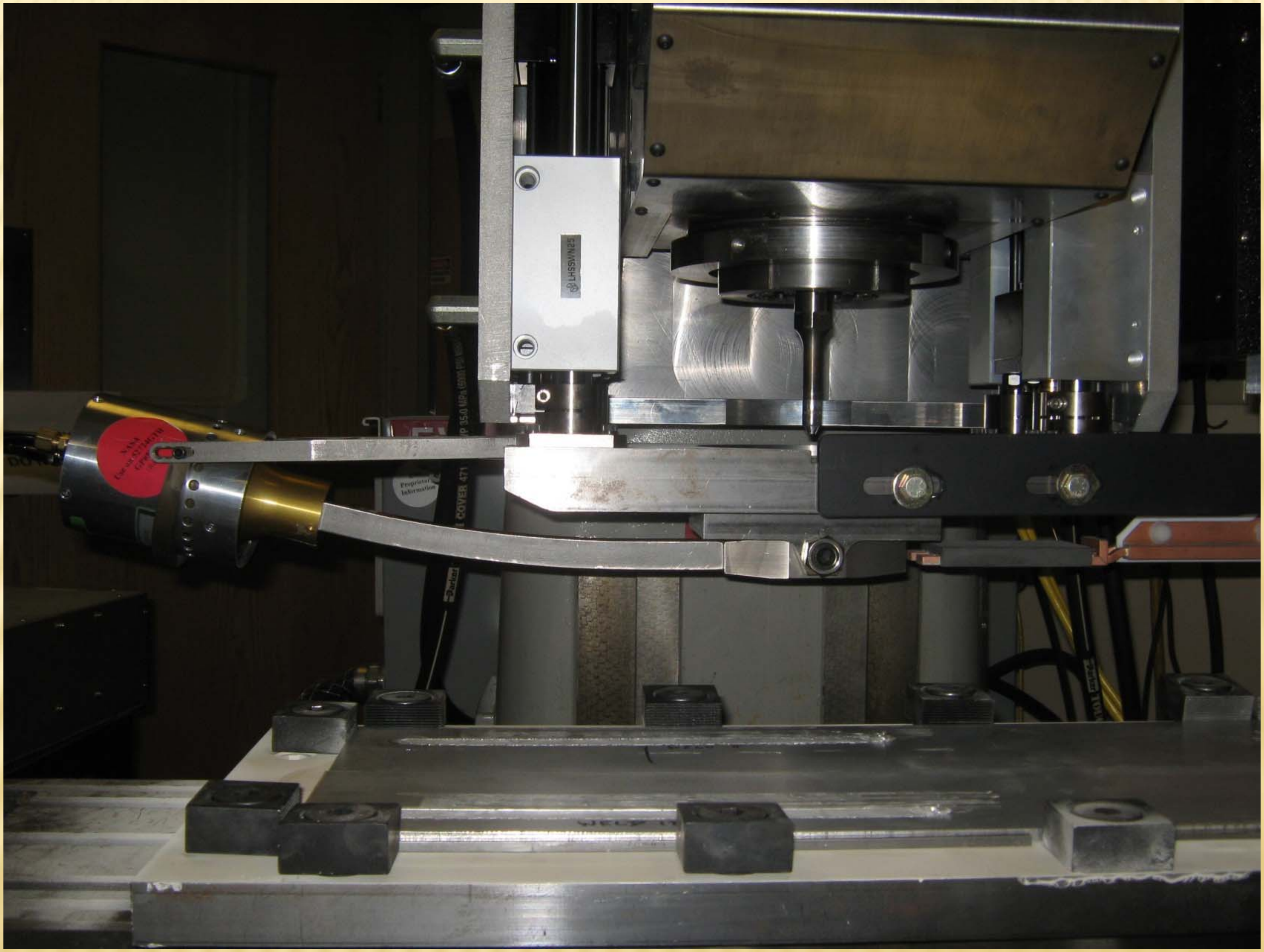
Robert.j.ding@nasa.gov

CURRENT USW DEVELOPMENT



Robert.j.ding@nasa.gov

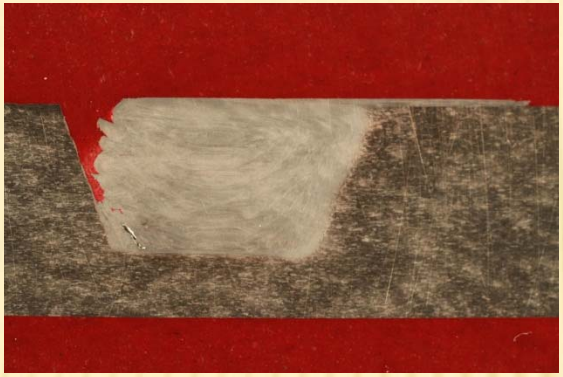
CURRENT USW DEVELOPMENT



Robert.j.ding@nasa.gov

CURRENT USW DEVELOPMENT

Sample 11-2 Bead on Plate



Sample 12-2 Bead on Plate

Sample 13-2 Weld Joint

- Weld 11-2 shows the difference in HPU being turned off during a weld
- Weld 12-2 shows stirring while HPU is on
- Weld 13-2 shows stirred weld joint
- The microstructures indicate that HPU energy assists in the heating of the weld nugget during the weld process.

Robert.j.ding@nasa.gov

USW SUMMARY

- With HPU power constantly "ON", the stir pin "stirred" the plasticized weld nugget
- HPU assisted with the heating of the weld nugget
- Advancing side of the weld nugget did not "stir" into the parent material
- Retreating side "stirred" into the parent material

Robert.j.ding@nasa.gov

USW SUMMARY - UPGRADES

System capabilities will include:

- Ability to “pulse” ultrasonic energy on and off
- Ability to adjust parameters real-time (travel speed, spindle RPM, US amplitude)
- Increase travel speed from 10 ipm to 20 ipm.
- Means to measure draw force.

Robert.j.ding@nasa.gov

USW SUMMARY – UPGRADES (cont.)

- Ability to record US power versus time
- Integrate a more powerful power supply
- Increase stiffness of Z axis drive and reduce head deflection
- Add linear encoder to better control tool penetration setting.
- Modify containment plate to eliminate gouging, increase vibration uniformity.

Robert.j.ding@nasa.gov

TSW SUMMARY

- The mechanical property results portray a material that possesses high plasticity and good damage tolerance behavior with weld properties very similar to the PM in two orientations.
- Based on survivability of the tool after 201 cm of weld and lack of tool debris, TSW'ing appears to be a viable method for producing long welds without detrimental tool wear.
- Further microscopy is needed to determine the overall temperature the material was subjected to during the TSW'ing process.

Robert.j.ding@nasa.gov

FUTURE TSW SYSTEM UPGRADES

- Incorporate closed loop temperature control
  - Select nominal “real time” welding temperature
  - Select optimal travel rate, RPM, IC power
  - Push “START”
  - If nominal temperature increases
    - Increase travel and/or decrease RPM and/or decrease induction coil power
  - If nominal temperature decrease
    - Decrease travel and/or increase RPM and/or increase induction coil power

Robert.j.ding@nasa.gov

TSW AND USW PROCESSES (AS WELL AS OTHER NASA OWNED TECHNOLOGIES) ARE AVAILABLE FOR LICENSING FROM NASA.

CONTACT SAMMY NABORS
TECHNOLOGY TRANSFER OFFICE
MARSHALL SPACE FLIGHT CENTER
256-544-5226

Robert.j.ding@nasa.gov