Approved For Public Release

Australian Government
Department of Defence
Defence Science and Technology Group

Additive Manufacturing for Aircraft Component Repair

W. Zhuang*, Q. Liu, R. Djugum and K. Sharp

Aerospace Division, DST Group

2016 Aircraft Airworthiness and Sustainment (Aus) Conference

Brisbane, 19-20 July 2016

Presentation Outline

1. Introduction
2. Laser Cladding for Aircraft Component Repair
3. Supersonic Particle Deposition and its Applications
4. Further Research and Technology Certification
5. Summary

1. Introduction

RAAF Ageing Platforms and Planned Withdrawal Date (PWD)

RAAF Assets	No. of A/C	Date into Service	Current PWD	Age @ PWD
F/A-18 A/B	71	1983	2020	37
P-3 Orion	19	1979	2019	40
PC-9/A	65	1987	2018	31
S-70B-2	16	1989	2019	30

Objectives of DST Group Additive Manufacturing (SPD and Laser cladding) Research Program:

1) To identify technology gaps for the purpose of aircraft component repair not only for geometry restoration but also structural strength of load-bearing components; and
2) To develop a certification test matrix and demonstrate AM in accordance with airworthiness standards, thereby enhancing aircraft structural integrity/safety and reducing ownership costs.

Ref: Zhuang et al, A Proposal for Transitioning Supersonic Particle Deposition for Aircraft Structural Integrity Repair, Aircraft Airworthiness and Sustainment (Australia), Brisbane, 23-25 July, 2013.

1. Introduction (cont'd)

DST Group Aircraft Advanced Repair Technologies

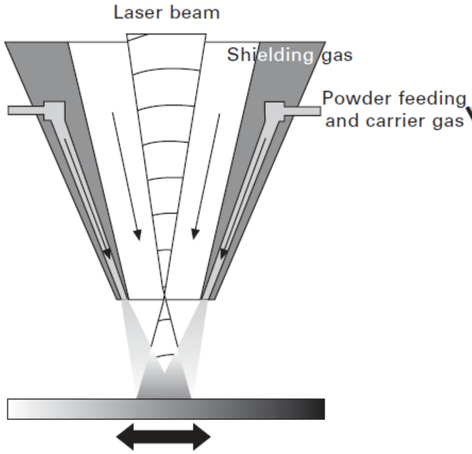
Technologies \ Applications	Repair of Corrosion	Repair of Wear	Geometry Restoration	Strength Restoration
Cold Spray	TRL 7-8	TRL 8-9	TRL 8-9	TRL ~5
Laser Cladding	TRL 7-8	TRL 8-9	TRL 8-9	TRL 4-5
Laser Additive Manufacturing	No data	TRL 3	TRL 6-7	TRL 4-5
Electronic Beam Melting	No data	No data	TRL 3	No data
High Velocity Oxygen Fuel	TRL 5-6	TRL 5-6	TRL 5-6	No data

Note: TRL - Technology Readiness Level, RC – Repair of Corrosion, RW - Repair of Wear, GR – Geometry Restoration and **SR – Strength Restoration/Structural Repair**, including both static and fatigue strength.

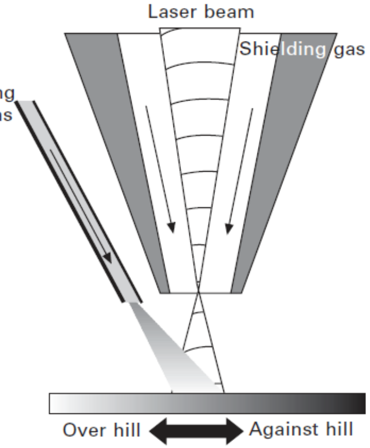
Ref: Pud, Liu, Zhuang, Gerrard and Sharp, Metallic material technologies for repair and fatigue life enhancement: Proposed Future Opportunities, DSTO-TR-2568, 2011

2. Laser Cladding Repair for Aircraft Components

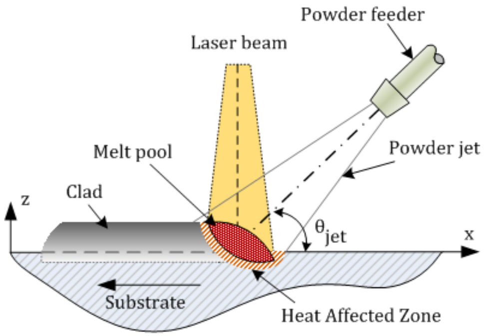
Laser Cladding or Laser Metal Deposition – How it Works

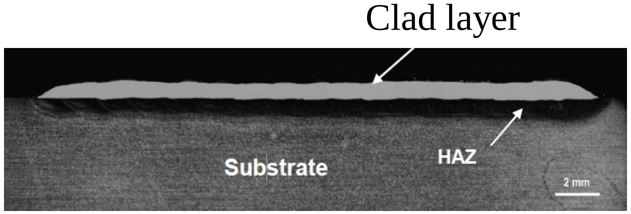


Coaxial laser cladding



Side laser cladding





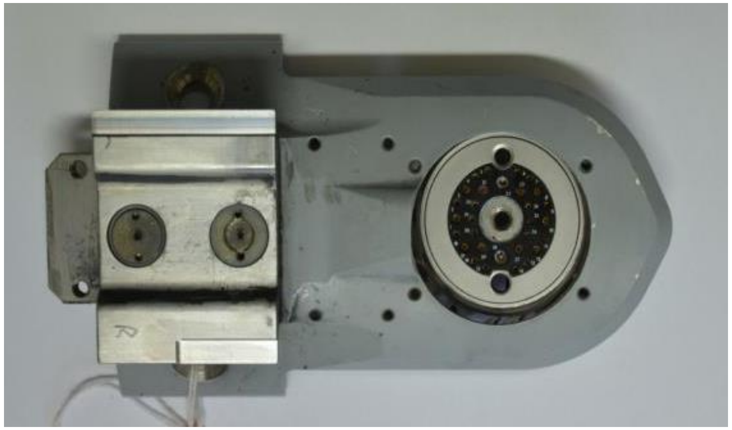
Ref: M. Brandt, Laser Additive Manufacture and Aerospace Industry, ICAMP8, Gold Coast, QLD, 2014

Laser Cladding for ADF Aircraft Components

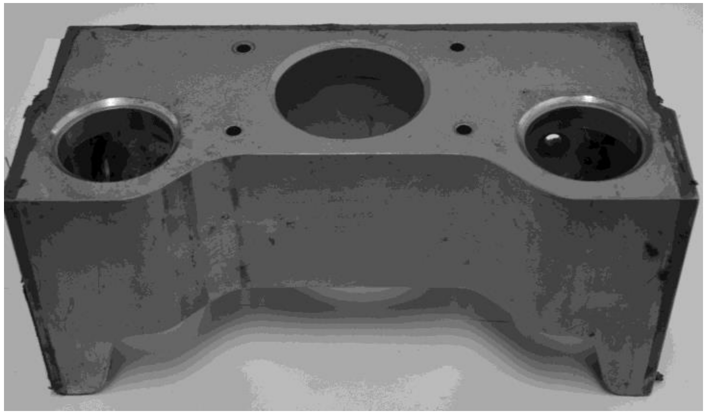
Components	Original Material	Repair Material	Restoration Requirements
FA-18 Engine Mount Bracket	Ti-6Al-4V	Ti-6Al-4V	Geometric restoration to restore wear damage
FA-18 Anti-Rotation Bracket	Stainless Steel (SS) 17-4PH	SS316 & SS420	Geometric restoration to restore wear damage
FA-18 Forward Hanger Assembly	cast SSPH13-8	SS17-4PH & SS420	Geometric restoration to restore wear damage
C-130J Shelf Bracket	Forged 4140 steel	SS17-4PH & SS420	Resurface with Stainless steel to reduce corrosion.
FA-18 MLG Housing	Forged AA2014	Al Alloys	Geometric restoration to restore corrosion damage

Components for Repair

F/A-18 Rudder Anti-Rotation Bracket
(certified & accepted by RAAF)



F/A-18/F Front Hanger Assembly
(laser cladding repaired, to be certified)



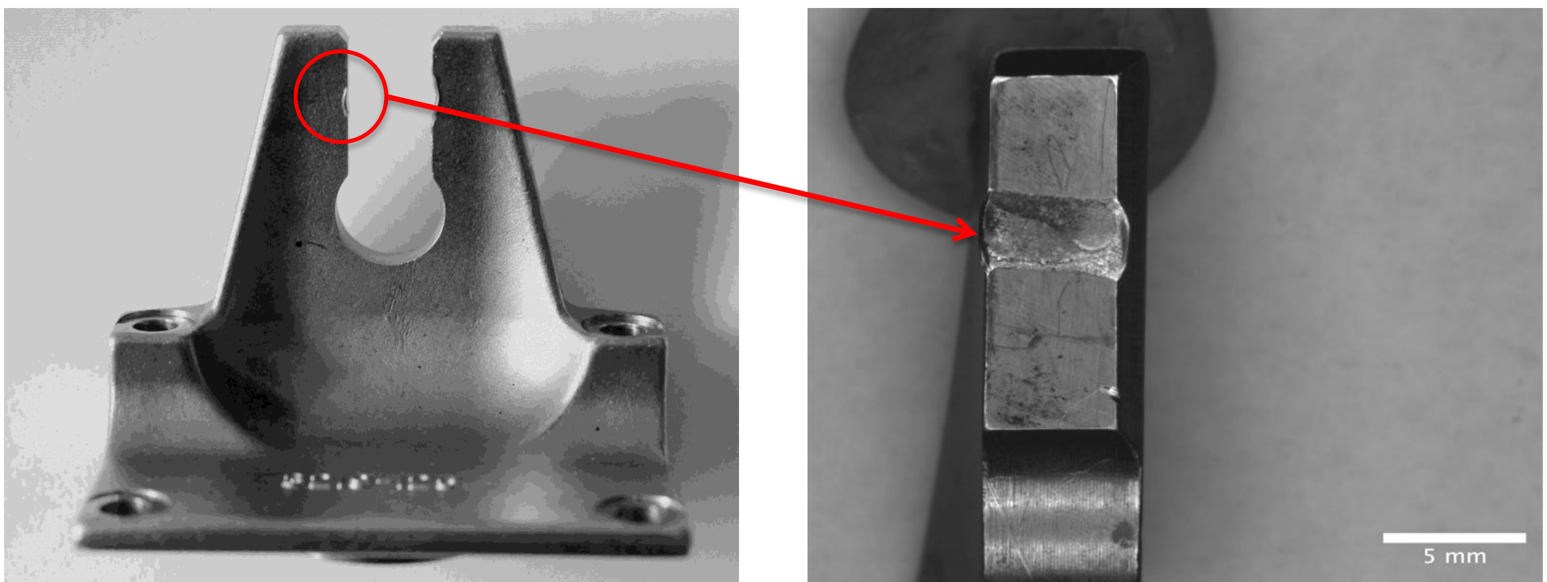
C-130J Shelf Bracket

F/A-18 Main Landing Gear Housing

Repair of F/A-18 Anti-Rotation Bracket

❖ Problem & Requirements:

- Unserviceable damage due to wear
- Precipitation-hardened stainless steel
- Geometrical restoration (No post heat treatment)
- Clad hardness to match component



Repair of F/A-18 Anti-Rotation Bracket

❖ Repair & Certification:

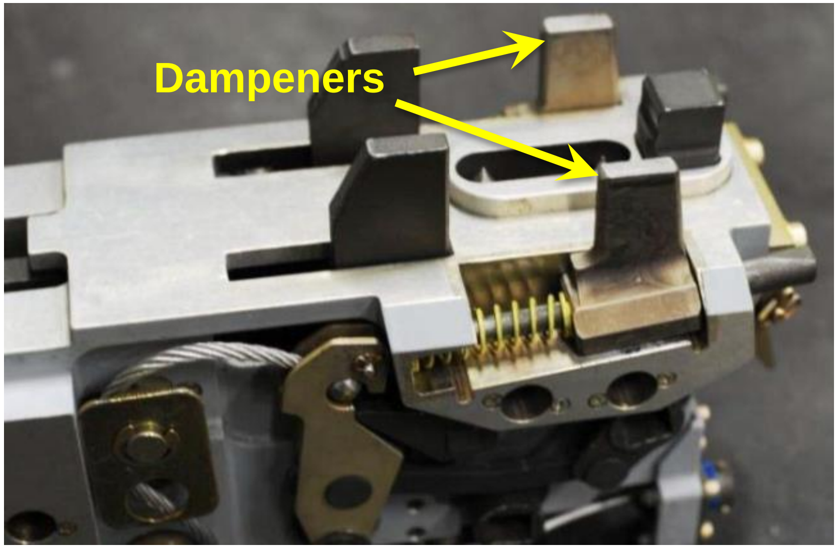
- Machine damaged area
- Develop a laser cladding repair (mixed powders)
- Clad & machine to tolerance
- TRL 9 (Certification approved, applied to aircraft)

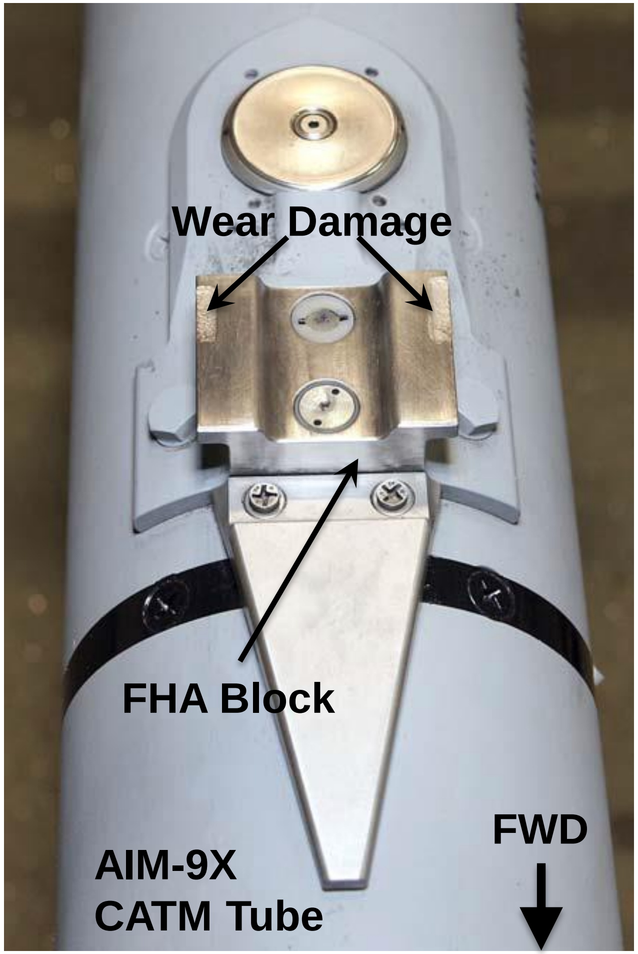
Repair of F/A-18F Forward Hanger Assembly

AIM-9X Missile Attachment Lug

❖ Problem & Requirements:

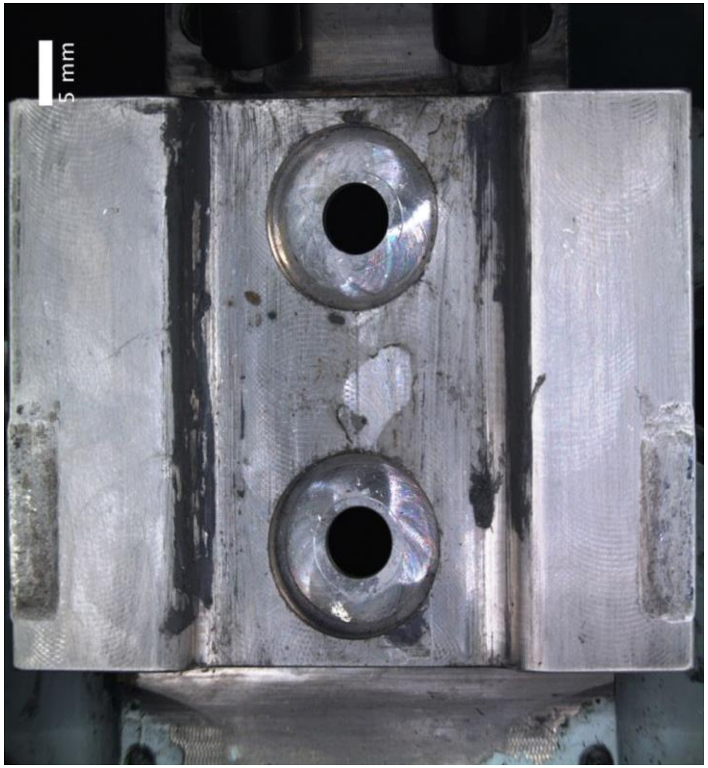
- Unserviceable damage due to wear
- Dampeners causing flange wear damage
- Allowable flange tolerance 0.25 mm
- Geometry restoration

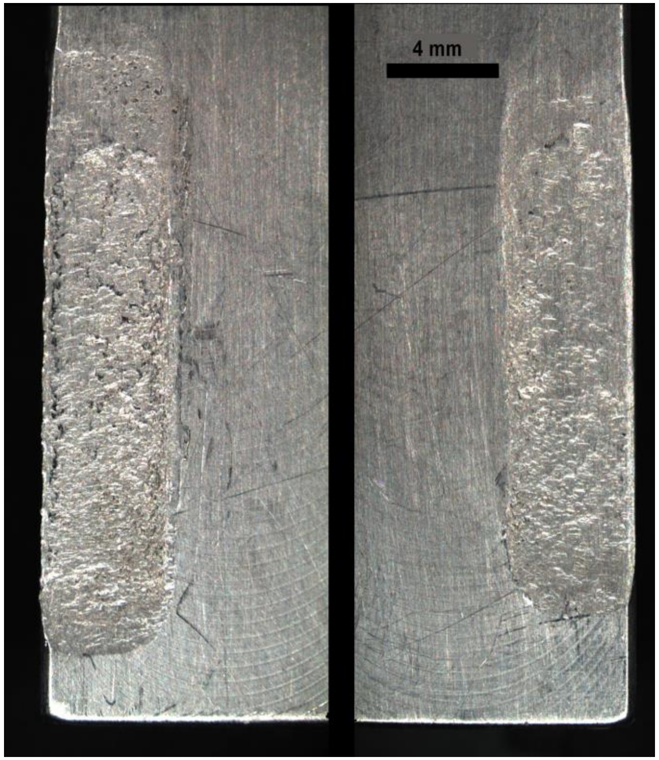




Repair of F/A-18F Forward Hanger Assembly

Damaged by Wear

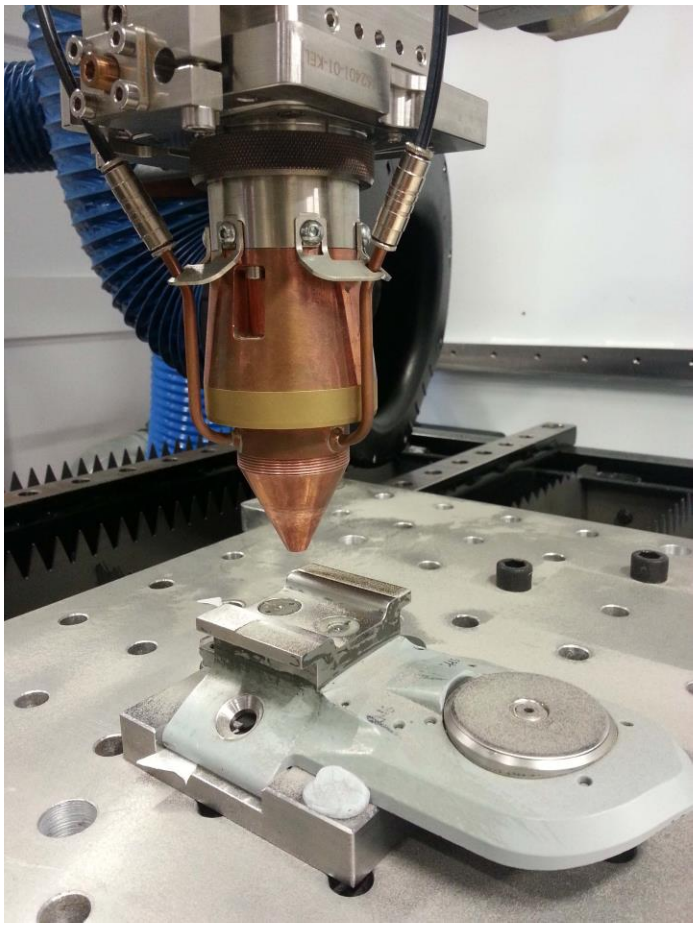


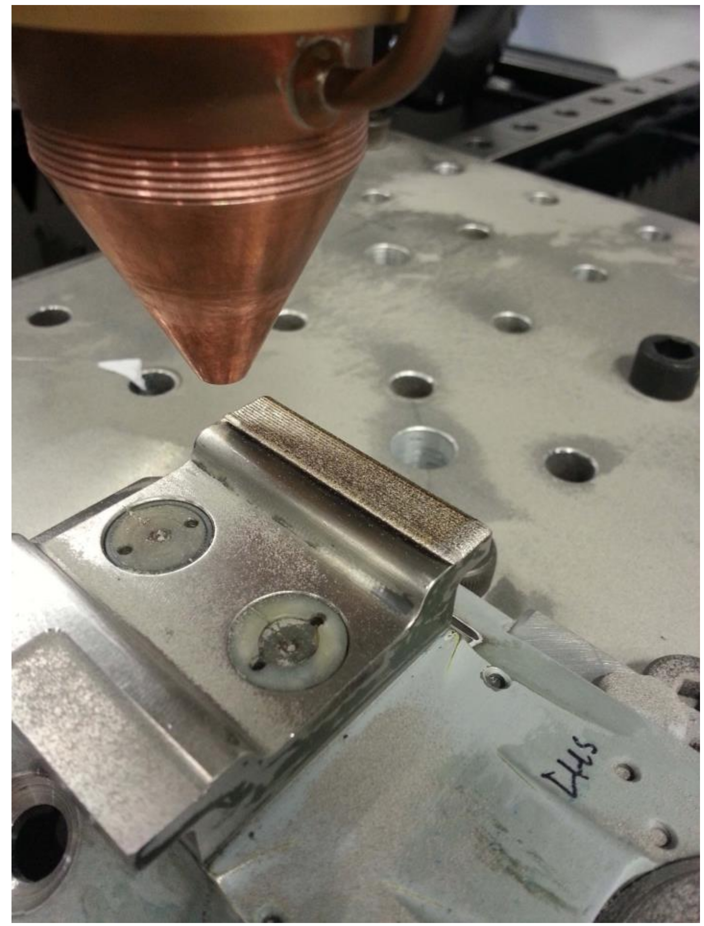


Material: Cast PH13-8 stainless steel

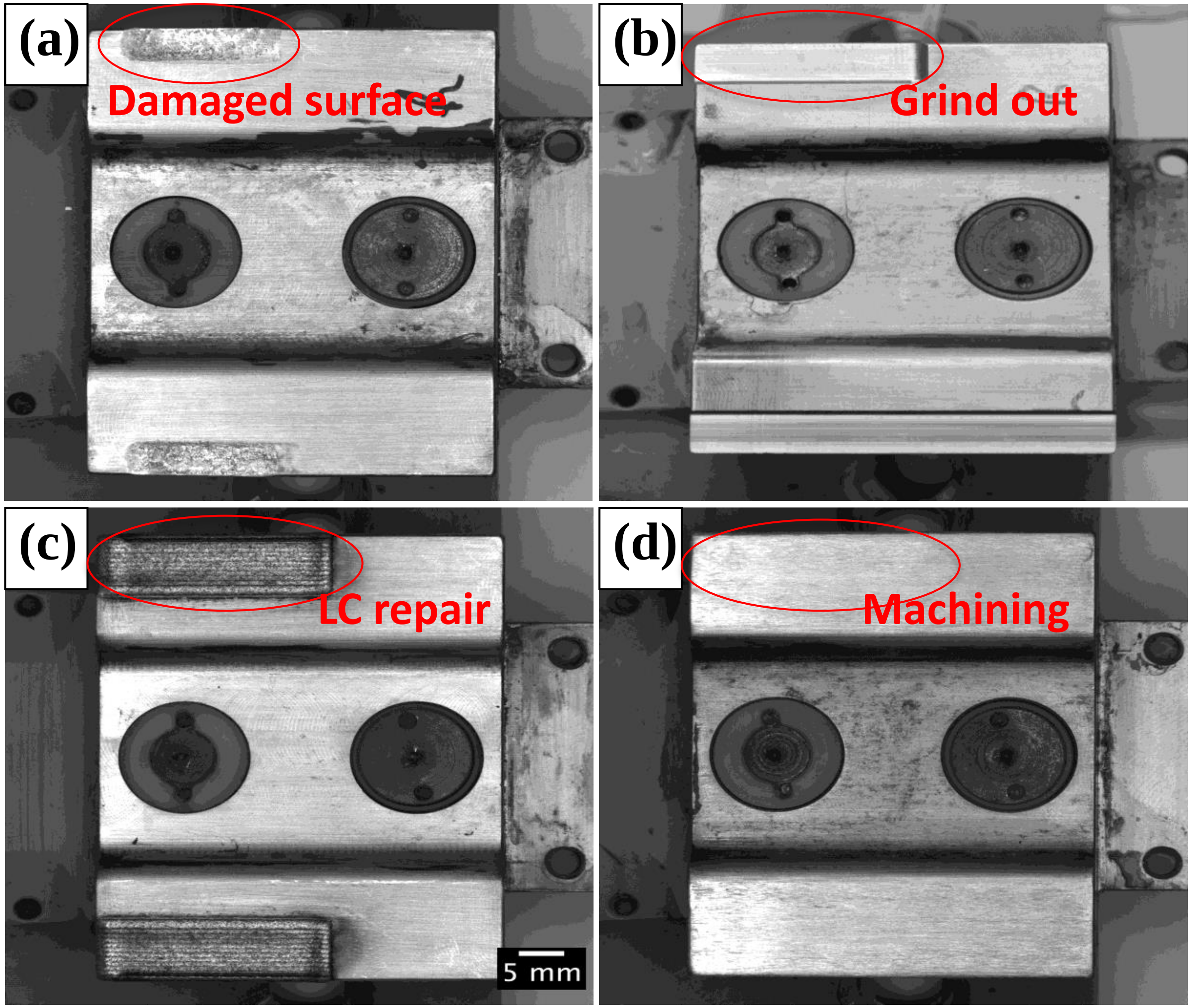
Repair of F/A-18F Forward Hanger Assembly

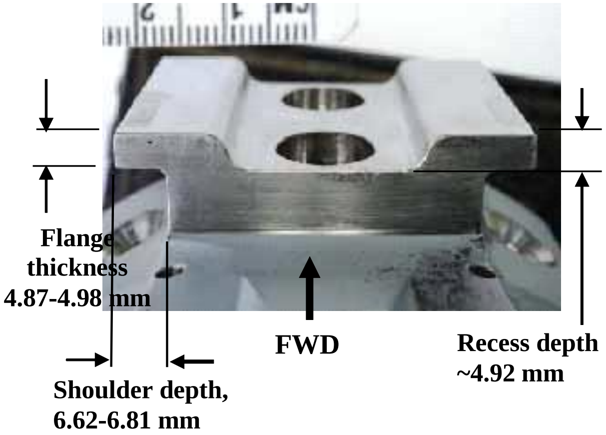
During Repair





Repair of F/A-18F Forward Hanger Assembly





Process developed:

* Matched on hardness

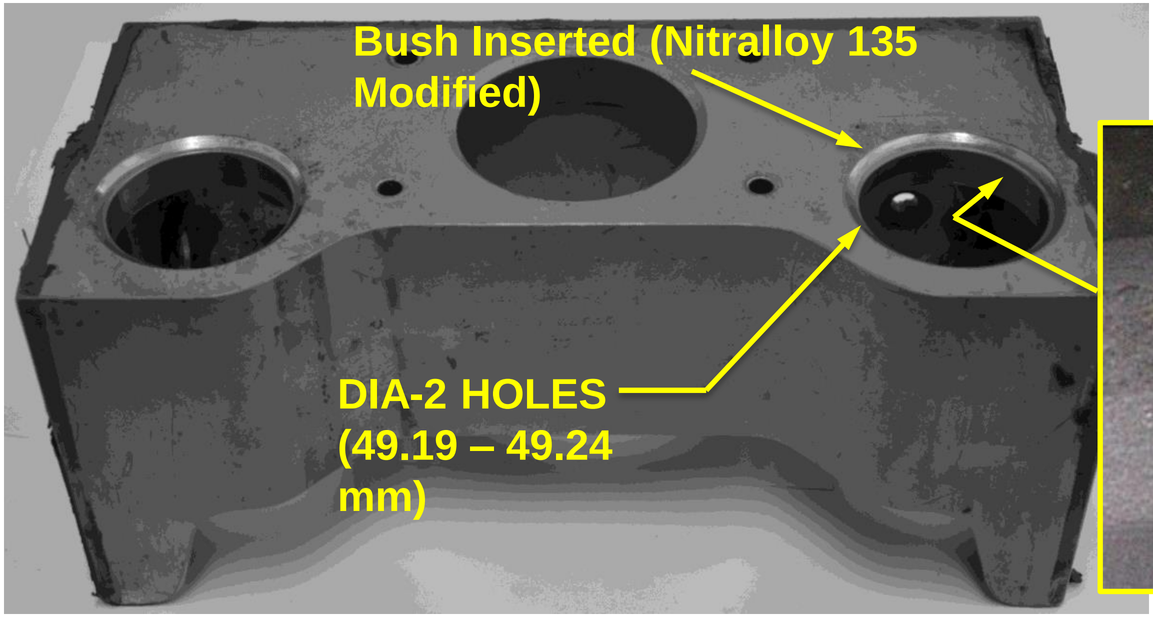
* Awaiting certification

DST GROUP
Science and Technology for Safeguarding Australia

Repair of C-130J Shelf Bracket

❖ Problem & Requirement:

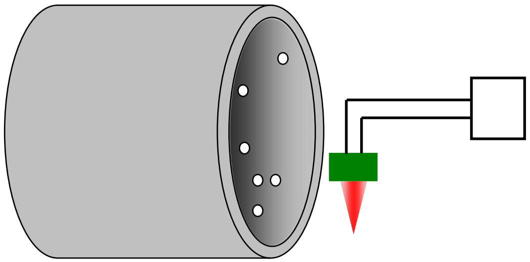
- Parts scrapped due to pitting corrosion
- AISI 4140 (forged steel)
- Very tight geometry tolerance

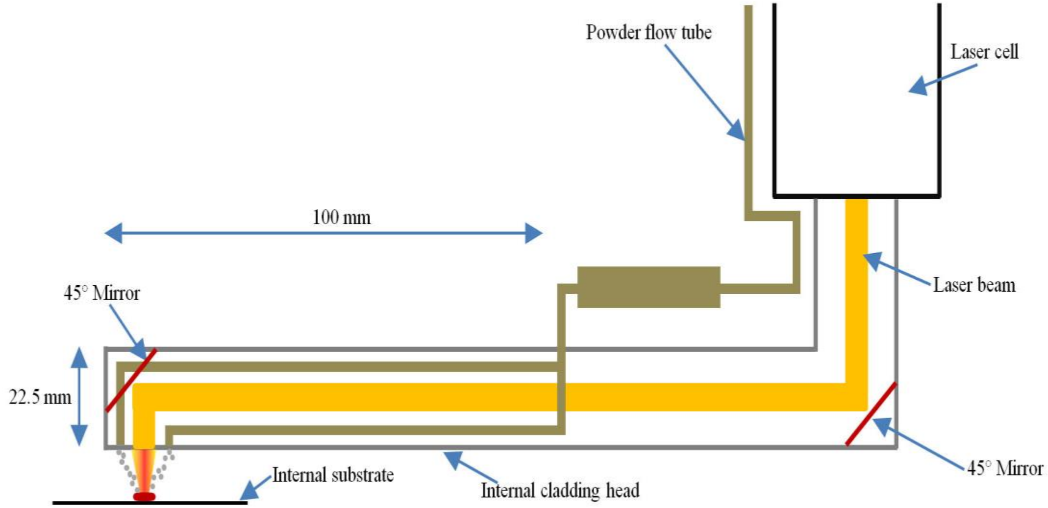


Repair of C-130J Shelf Bracket

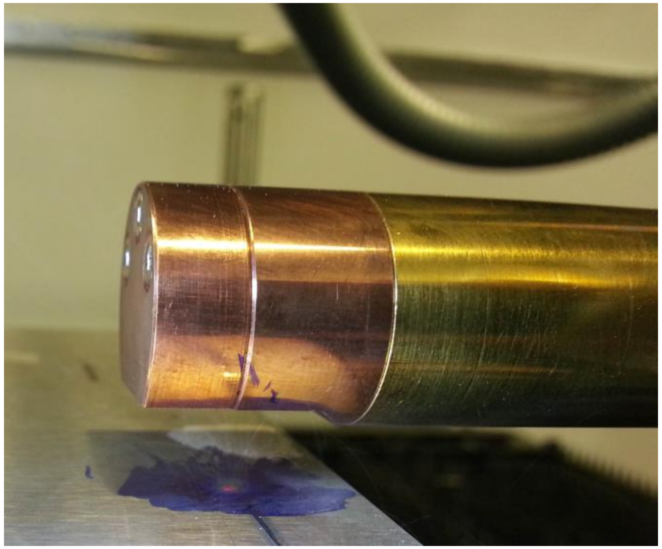
❖ Repair Strategy (solution):

- Internal Repair
- Cladding nozzle developed with ILT
- Stainless steel powder





Schematic of a cladding nozzle for the internal repair, designed by Fraunhofer Institute of Laser Technology



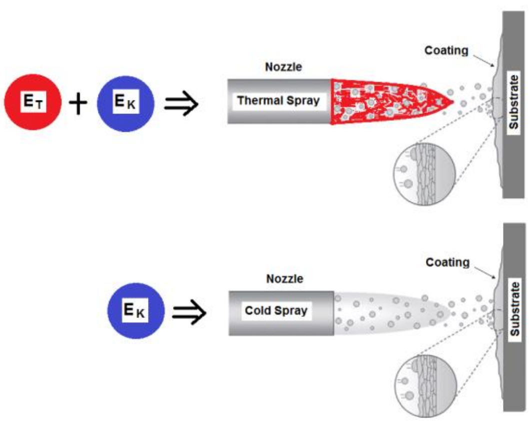
(Source: RMIT, unpublished info, 2015)

DST GROUP Science and Technology for Safeguarding Australia

3. Supersonic Particle Deposition and Applications

A Brief History of Supersonic Particle Deposition or Cold Spray

Anatolii Papyrin



CS vs Thermal Spray

1) Supersonic Particle Deposition (SPD) or Cold Spray (CS) was accidently discovered by Russian scientists, Anatolii Papyrin et al. when studying rocket engine models subjected to a supersonic two-phase flow (gas + solid particles) in a wind tunnel in the mid-1980s.

2) The CS then became a material deposition technology by spraying typical 1-50 μm particles which are accelerated by a supersonic jet of working gas to speeds of 300-1200 m/s, normally at a temperature lower than the melting point of the material.

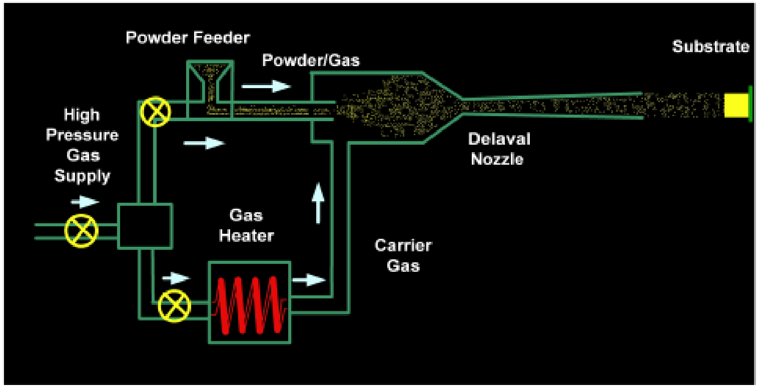
3) The CS coatings have little porosity, few oxides, and reasonably high bond strength, and importantly, high deposition efficiency.

Ref: A. Papyrin et al, Cold Spray Technology, Elsevier, 2007

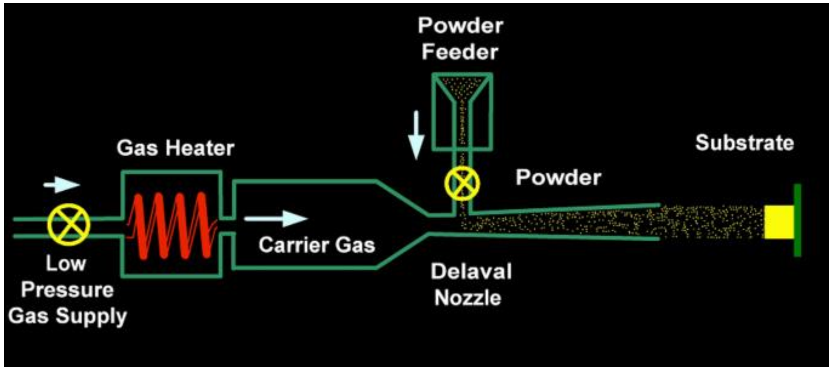
3. SPD and its Applications (cont'd)

Types of Cold Spray Systems

1. By Process Pressure

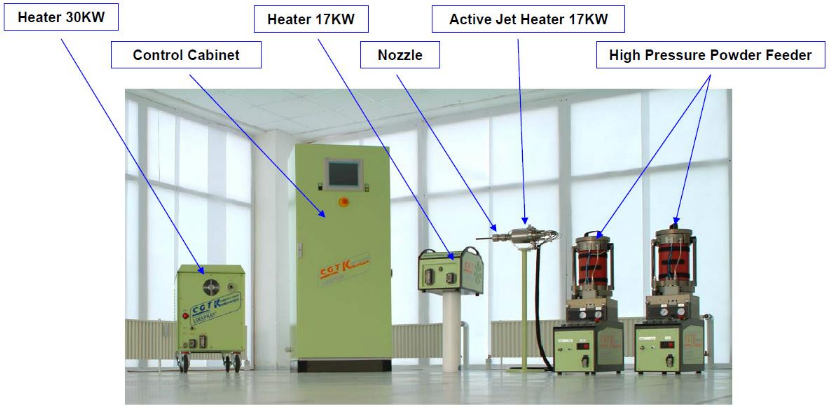


High Pressure Cold Spray (HPCS) such as MetalFinishing up to 70 Bar/1000 psi.



Low Pressure Cold Spray (LPCS) such as CenterLine around 10 Bar/140 psi.

2. By Mobility



Stationary such as CGT KINETIKS.

DSTG/RBE Portable system.

ARL using a handheld system for a rotorcraft component.

Current Capabilities and Application

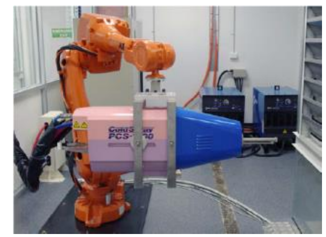
In-country Capabilities (CS Systems)

1. Government

-- DSTO/RBE – Portable CS System

- CSIRO

CGT Kinetiks 3000 & 4000 Series



Japan Giken PCS 1000

2. Academia

The University of Queensland Australia

Inovati Kinetic Metallization (LPCS)

3. Industry

Rosebank Engineering Australia

CGT Kinetiks 8000 with ABB robot for F/A-18 Centre Barrel

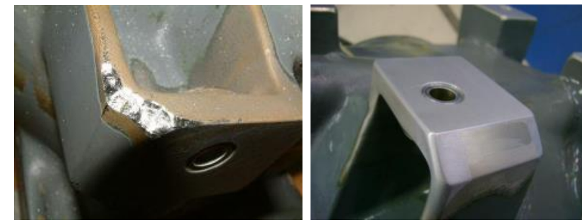
DSTO/RBE Portable CS System for RAN Seahawk GR

Current Capabilities and Application (cont'd)

In-country Applications (CS for GR)

Rosebank
Engineering Australia

RBE with DSTO support has certified CS for NASPO Seahawk applications (for geometry restoration).



IGB Mounting Foot – Before & After CS

CS applied to 6 Input module webs and mounting faces

CS applied to 4 main module sumps and Flight control pads

CS applied to 8 accessory module mounting faces for corrosion protection and geometry restoration

CS applied to 5 TRGB feet

CS applied to 4 Intermediate Gearbox (IGB) feet for corrosion protection and geometry restoration

Total 27 applications on Seahawk and no failures over hundreds flight hours since 2009

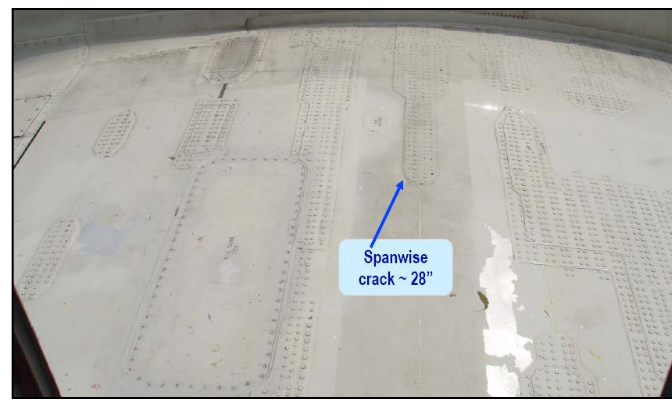
Refs: Matthews, Cold Spray - An Australian Update , Cold Spray Action Team Meeting, 18-19 June 2014.
Darren et al, Cold spray coating technology for the corrosion protection and repair of JSF / aerospace components, ASM TSS Cold Spray, USA, 2007.
Darren et al, S&T Support to Rosebank Engineering P/L Cold Spray Coating Facility - 2007/08, DSTO-CR-2008-0408, 2009

Current Capabilities and Application (cont'd)

In-country Applications (The CS for Structural Repair-SR)

Trial on F/A-18 centre barrel with 12 CS Doublers

P-3C fuselage lap joints corrosion repair



Refs: Matthews et al, Application Of Supersonic Particle Deposition to Enhance the Structural Integrity of Aircraft Structures, International Conf. on Airworthiness & Fatigue , Beijing, China., 25-27 March 2013.
Jones et al, SPD as a means for enhancing the structural integrity of aircraft structures, International Journal of Fatigue, 2014.
Zhuang et al, DSTO FINAL test demonstration on aircraft repair technology – SPD, DSTO Minute 2013/1089275/1/005, 2013.

Current Capabilities and Application

Overseas Capabilities (CS Systems and Manufacturers)

1. Americas

**1). ASB Industries Inc.
Kinetiks™ 4000/8000 Series CS System**

Kinetiks™ 8000 Series
Perssure: 40 bar
Temperature: 1000 ^{o}C
Dep. Rate: 12-14 kg/h
Dep. Efficiency: 95%

2). Centerline

Centerline SST CS
Perssure: 7-35 bar
Temperature: 25-550 ^{o}C

3). Inovati

Inovati KM Mobile System
Perssure: ~10 bar
Temperature: 120-660 ^{o}C

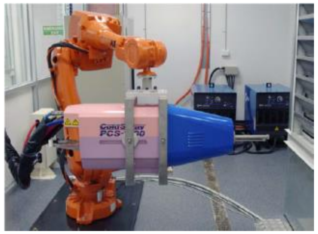
2. Europe

1). Sulzer Switzland purchased Gernamy CGT Cold Spray in 2012

CGT 4000 Series
Perssure: 40 bar
Temperature: 1000 ^{o}C
Dep. Rate: 12-14 kg/h
Dep. Efficiency: 95%

3. Asia/Pacific

1). Japan Giken PCS 1000

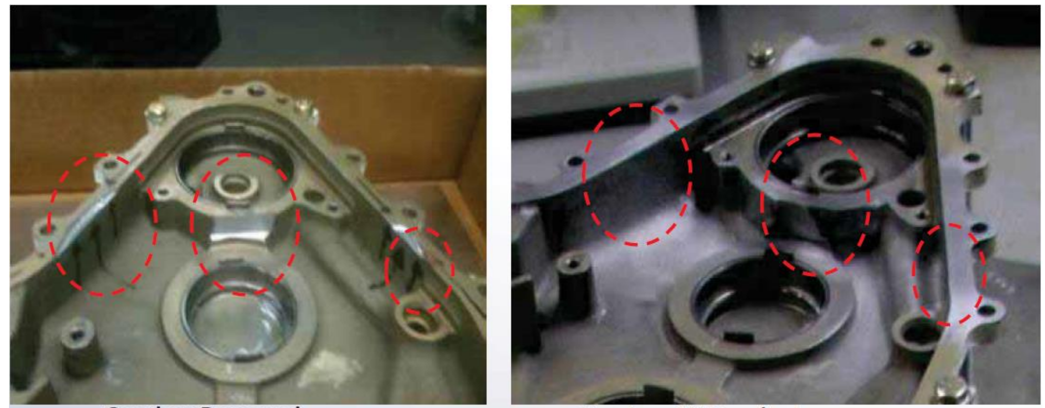


Giken PCS 1000
Perssure: 50 bar
Temperature: 1000 ^{o}C
Dep. Rate: 45 kg/h

Current Capabilities and Application (cont'd)

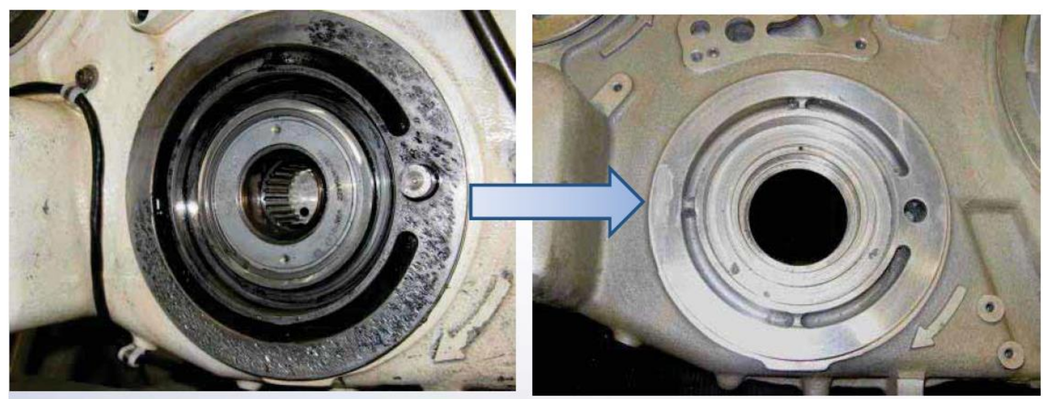
Oversea Development (US Navy CS Applications to F/A-18)

- F/A-18E/F Aircraft Mounted Accessory Drive (AMAD) Main Housing (hydraulic pad geometry restoration of cast A357 Al Alloy).



Gearbox Damaged | Gearbox CS Repaired

- F/A-18E/F AMAD Main Housing (gear failure repair of cast A357 Al alloy).



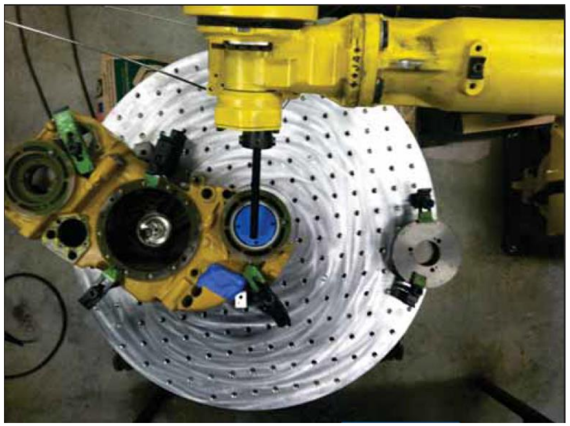
Gearbox Damaged | Gearbox CS Repaired

Refs: F. Lancaster, NAVAIR Cold Spray Initiative Update, Cold Spray Action Team Meeting, Worcester Polytechnic Institute, MA, USA, 2014

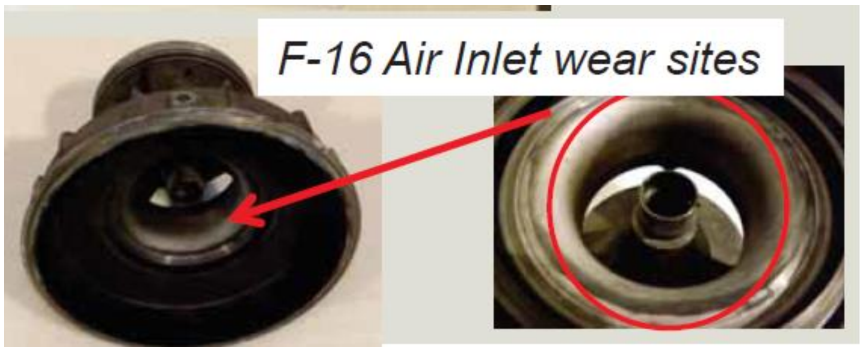
3. SPD Current Capabilities and Application (cont'd)

Oversea Development (US Air Force CS Applications)

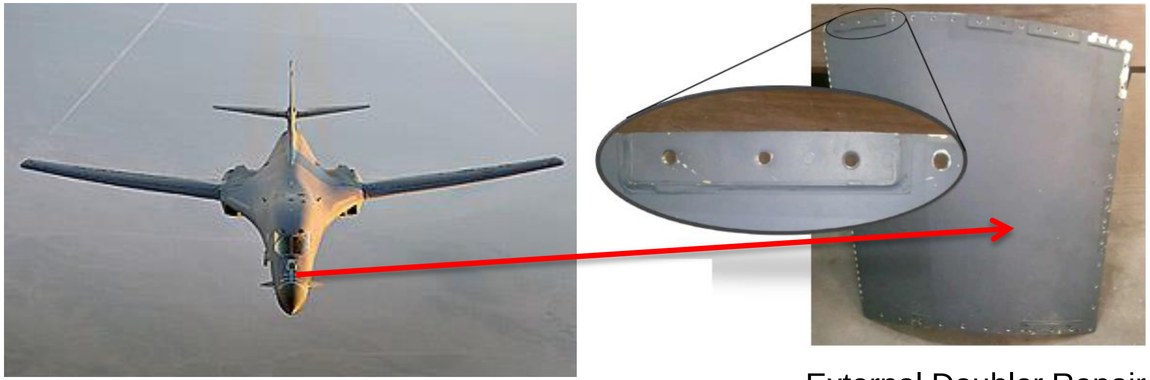
(1). F-15 AMAD – Magnesium Housing Repair



(2). F-16 Air Inlet Repair



(3). B1 Bomber-FEB Panel Repair (8 aluminum panels per aircraft)



External Doubler Repair

After CS repair before painting

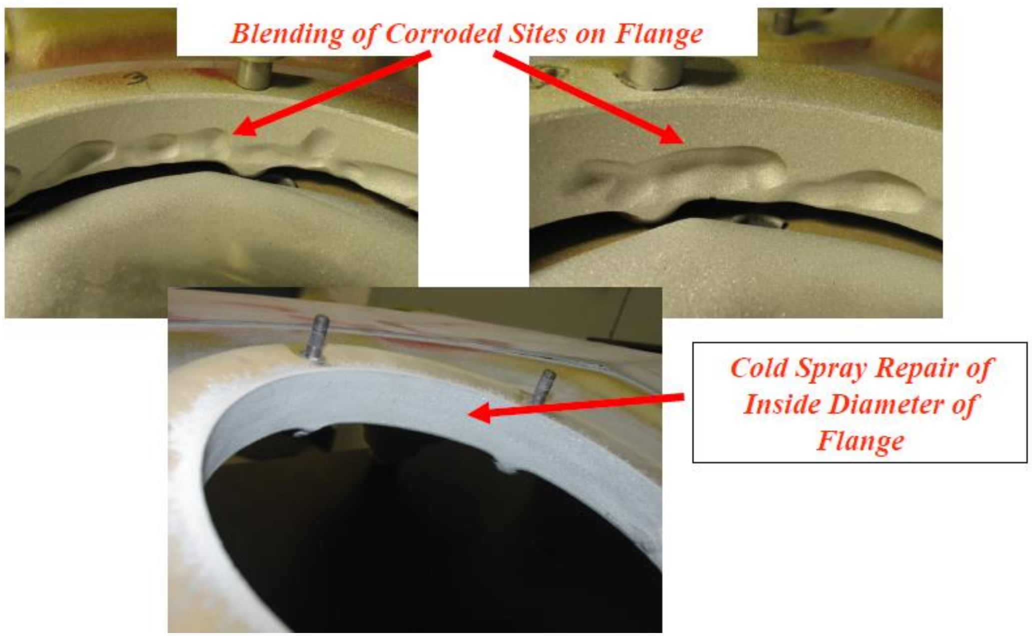
After painting

Refs: C. Widener, B1 Bomber-FEB Panel Repair by Cold Spray, Cold Spray Action Team Meeting, Worcester Polytechnic Institute, MA, USA, 2012

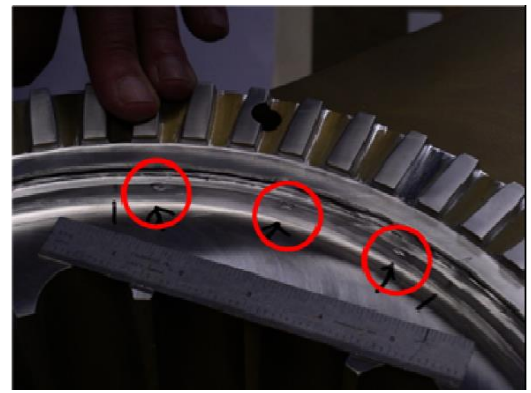
3. SPD Current Capabilities and Application (cont'd)

Oversea Development (US Army CS Applications)

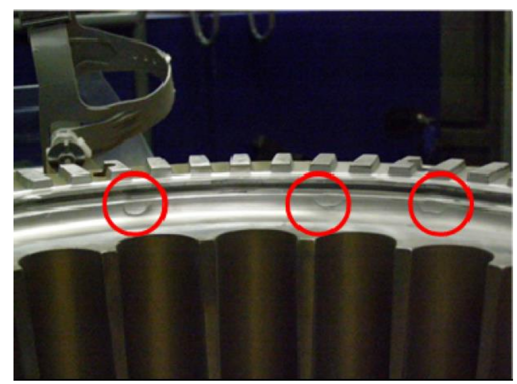
(1). UH-60 Black Hawk Helicopter -Main Gearbox Repair



(2). Reclamation of the Apache Helicopter Mast Support



Corrosion pits in lower lip of snap ring groove

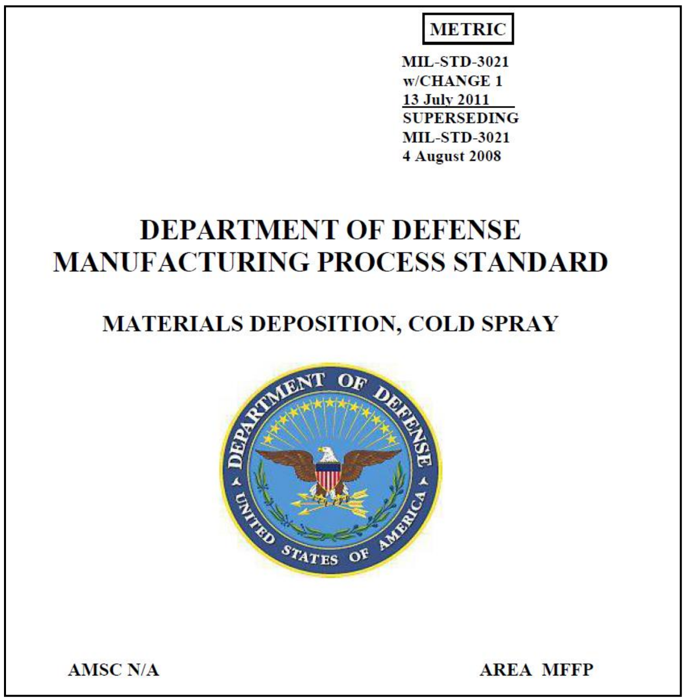


After CS fill and dimensional restoration

Ref: V. K. Champagne, P.F. Leyman, and D. J. Helfritch, Magnesium Repair by Cold Spray, ARL-TR-4438, Army Research Laboratory, May 2008..

4. Further Research and Technology Certification

- Little useful technical details and certification information are available although SPD/CS has been widely used for geometry restoration (GR).
- No Standard for SPD/CS as aircraft structural repair that addresses Aircraft Structural Integrity (ASI) and airworthiness requirements.



METRIC

MIL-STD-3021
w/CHANGE 1
13 July 2011
SUPERSEDING
MIL-STD-3021
4 August 2008

DEPARTMENT OF DEFENSE
MANUFACTURING PROCESS STANDARD

MATERIALS DEPOSITION, COLD SPRAY

AMSC N/A   AREA MFFP

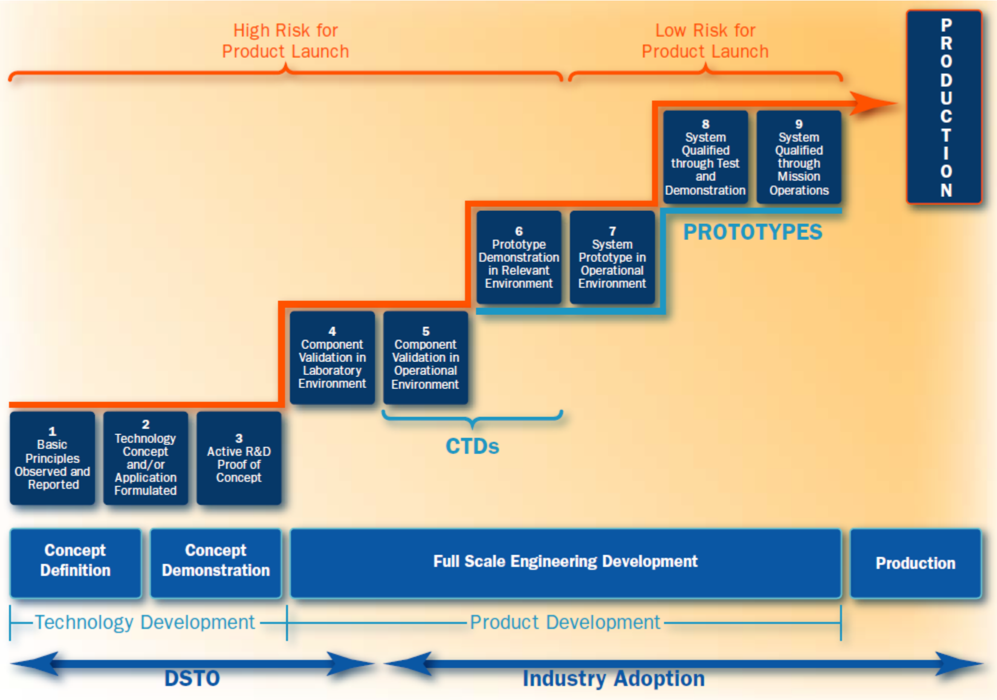
1. MIL-STD-3021 ensures the SPD/CS process for restoring dimensional discrepant parts, or parts requiring protection from corrosion and wear.
2. There is no detailed technical requirements and test procedures provided.

Ref: Zhuang, Proposal of Development of SPD for Aircraft Structural Repairs, DGTA SPD Technology Transition Working Group, 11th Dec 2012.

Challenges of AM as an Aircraft Structural Repair

Why Repair Analysis is Required?

- All major repairs (including using LC and SPD) must comply with current certification basis of the affected aircraft;
- The scope of the repair analysis depends on the consequences of failure; and
- The repair process must be verified by analysis, inspections, and/or tests that will dictate the TRL of the repair technology.



DSTO Technology Readiness Level (TRL) Chart

Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

Challenges of SPD as an Aircraft Structural Repair

Technology Gaps of SPD for SR

Substrate / Powder	ZE41A	Cast Al A357	AA2024-T3	AA7075-T6	AA7050-T7451
Mg	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Al pure	**TRL-GR 8-9** **TRL-SR 4-5**	**No data**	**TRL-GR 8-9** **TRL-SR 4-5**	**TRL-GR 8-9** **TRL-SR 4-5**	**No data**
AA 6061	**TRL-GR 8-9** **TRL-SR 4-5**	**TRL-GR 8-9** **TRL-SR 4-5**	**TRL-GR 8-9** **TRL-SR 4-5**	**TRL-GR 8-9** **TRL-SR 4-5**	**No data**
AA 7075	**TRL-GR 8-9** **TRL-SR 4-5**	**No data**	**No data**	**TRL-GR 4-5** **TRL-SR 4-5**	**N/A** **TRL-SR 4-5**
AAl 7050	**No data**	**No data**	**No data**	**TRL-GR 4-5** **TRL-SR 4-5**	**N/A** **TRL-SR 4-5**

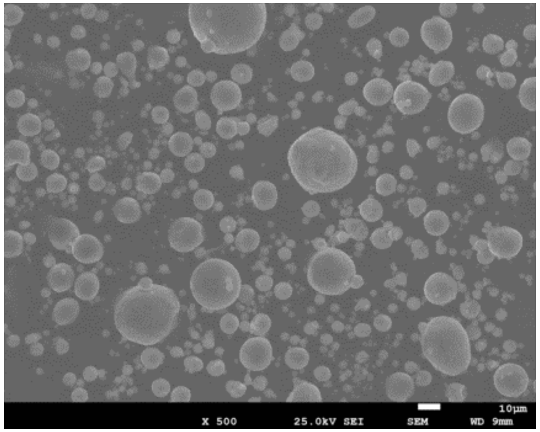
Note: Many aircraft load-bearing components are made of either 2xxx or 7xxx AA. SAE 4130 Steel not included.

Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

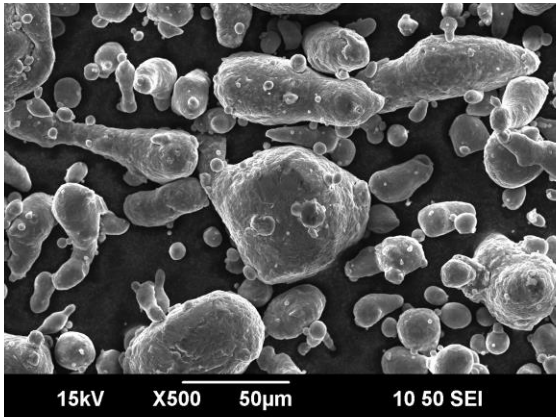
Further Research in SPD for Structural Repair

Need to Establish Specification for Quality Control of the SPD Powders

- Micromorphology (Irregular shape vs spherical particles)
- Chemical composition (Contamination and impurities)
- Size distribution (the smaller standard deviation the better the quality of SPD coating)
- Flowability



Powder Morphology of AA7075

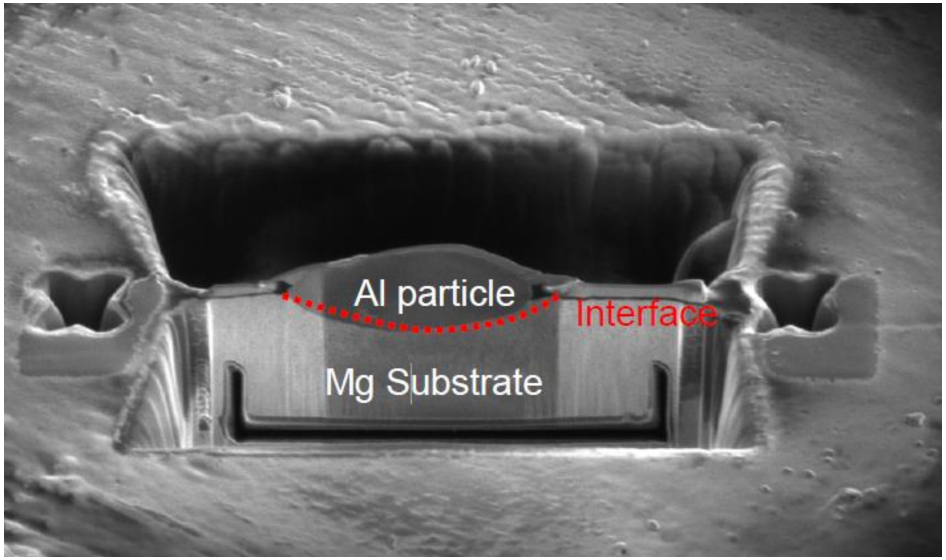


Powder Morphology of AA7050

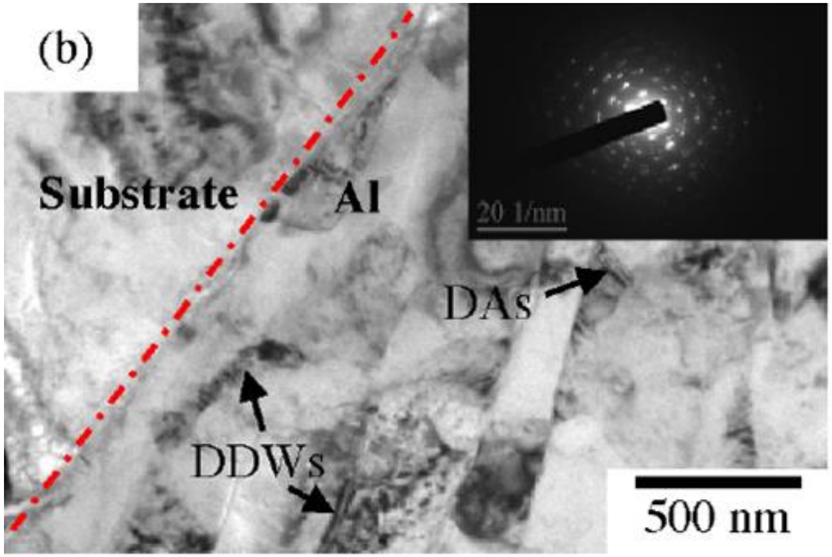
Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

4. Further Research in SPD for SR

Need a Better Understanding of Bonding Mechanism and Interface



TEM membrane prepared by FIB milling for the observation of adiabatic shear plastic deformation at the interface of the particle and substrate.

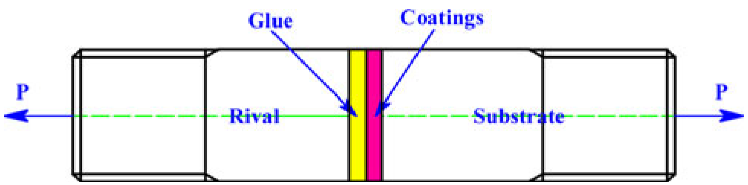


Typical conventional TEM microstructure along the interface of Csed Al and the AZ91 substrate, the insert diffraction pattern is from Al side adjacent to the interface.

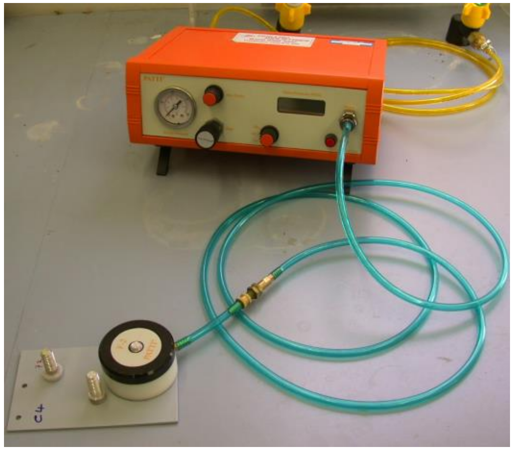
Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

Further Research in SPD for SR

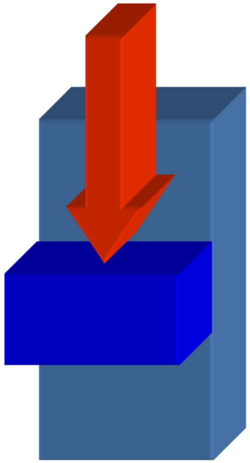
Need Innovative Approach to Assess Bond Strength

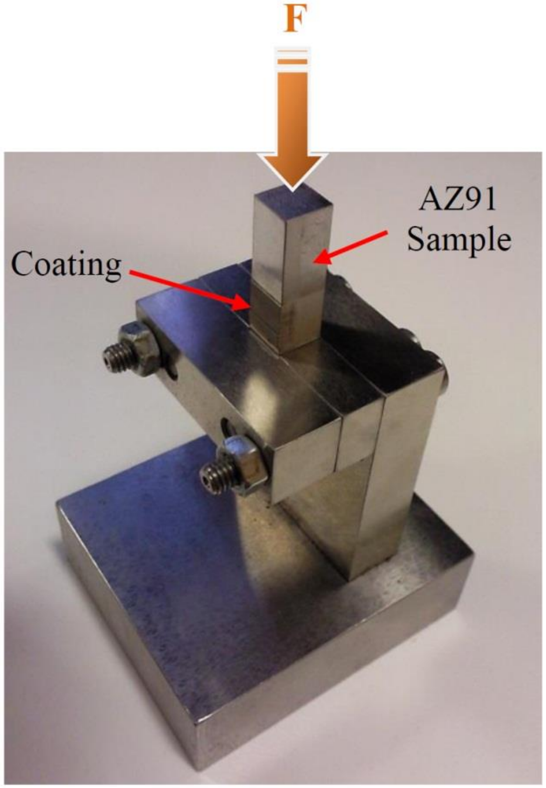


ASTM C633 bond strength testing is limited by adhesive strength.



PATTI adhesion testing is also limited by adhesive strength.





The University of Queensland lug shear test rig for high bond strength testing (no adhesive required).

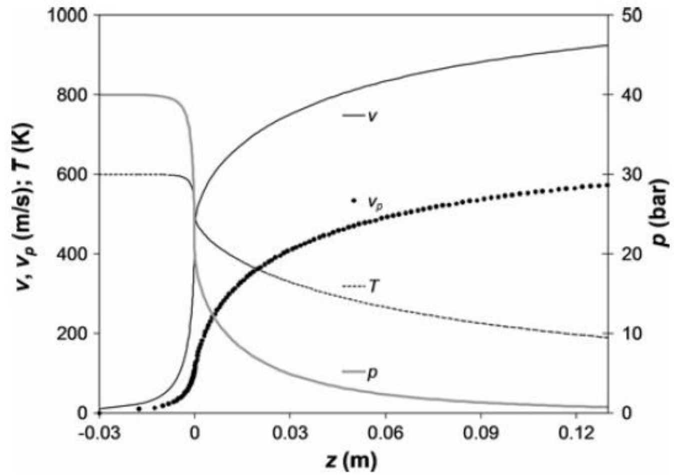
Ref: *W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.*

4. Further Research in SPD for SR

Optimisation of the Complex Interdependent SPD Process

The Isentropic Flow Model for the CS process parameters

$$v_p \frac{dv_p}{dz} = \frac{3}{4} C_d \frac{\rho(v - v_p)|v - v_p|}{\rho_p d_p}$$



A parametric plot of υ, υp, T, and ρ versus z.

υp – In-flight particle velocity.

υ – gas velocity.

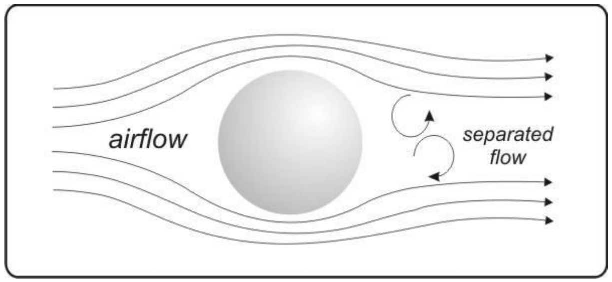
z - the axial distance from the nozzle throat.

Cd - Drag coefficient.

ρ - Gas density.

ρp - Particle density.

T - Gas temperature



$$F_D = \frac{1}{2}\rho A C_D v^2$$

drag force

density

acceleration

drag coefficient

velocity

Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

DST GROUP Science and Technology for Safeguarding Australia

4. Further Research in SPD for SR

The Certification Test Matrix for SPD for SR

ID	Test Title	For GR	For SR	Test Objectives	Test Specification and Standard
1	Compression	Y	Y	To determine the compressive strength, the stress-strain curve, and compressive failure such as buckling and coating spalling.	ASTM E9-09 Standard Test Method for Compression Testing of Metallic Materials at Room.
2	Tensile for mechanical properties	Y	Y	To determine yield strength, yield point elongation, tensile strength, elongation, and reduction of area.	ASTM E8_E8M-11 Standard Test Methods for Tension Testing of Metallic Materials.
3	Tensile for bonding strength	Y	Y	To determine the bonding strength of the CS coating to substrate or cohesion strength of the coating in tension normal to the surface.	ASTM C633-2008 Standard Test Method for Adhesion and Cohesion Strength of Thermal Spray Coatings.
4	Shear for bonding strength	N	Y	To assess the degree of adhesion of the CS coatings to substrates, or the internal cohesion of the CS coating in shear, parallel to the surface plane.	ASTM F1044-05 Standard Test Method for Shear Testing of Calcium Phosphate Coatings and Metallic Coatings.
5	Impact Testing	Y	Y	To ensure that the impact properties of the CS coatings are equivalent or better than the substrate.	ASTM D5420 - Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact).
6	Corrosion	Y	Y	To ensure the corrosion resistance of the CS coatings is equivalent or better than the substrate and to assess whether adequate corrosion protection of the substrate exists.	ASTM B117 - Standard Practice for Operating Salt Spray (Fog) Apparatus.
7	Residual Stress Measurement	N	Y	To ensure no significant tensile residual stresses in the coatings and the interface.	To be dependent on the residual stress measurement technologies.
8	Constant Amplitude Fatigue	Y	Y	To assess the fatigue strength of the CS repaired samples in a laboratory environment.	ASTM E 466 - Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Test of Metallic Material
9	Representative Fatigue Testing under Spectrum Loading	N	Y	To assess the fatigue strength of the CS repaired representative samples in relevant flight operational conditions.	To be developed by DSTO IAW the relevant aircraft certification structural design standard and structural repair manual.
10	Full-scale Fatigue Test Demonstration	N	Y	To demonstrate fatigue strength and repair capability of CS repaired aircraft components subjected to representative flight spectrum loading.	To be developed by DSTO IAW the relevant aircraft certification structural design standard and structural repair manual.

Ref: W. Zhuang, Keynote: Opportunities and Challenges for SPD in Aircraft Structural Repair, ICAMP-8, Gold Coast, QLD, 2014.

5. Summary

1) The current status of AM technologies (LC and SPD) for repairing damaged aircraft components, particular for load-bearing components in accordance with aircraft certification structural design standards has been provided.

2) The challenging issues of using AM technologies for repairing aircraft components were identified and discussed.

3) No Silver Bullet or single technology will solve all problems. In other words, a repair technology should be used most applicable to the material of component and its desired properties.

4) Future research and technology certification have been proposed and discussed. These provide some guidelines for the Defence research program in AM-based repair technologies.

Australian Government
Department of Defence
Defence Science and Technology Group

Thank You !