Messier-Dowty Inc.
Stellite Coatings

Evaluation of HVOF Coatings on Carrier Aircraft

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HCAT Meeting
January 24, 2006

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **24 JAN 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Evaluation of HVOF Coatings on Carrier Aircraft**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Messier-Dowty Inc.,SAFRAN Group,574 Monach Avenue,AJAX, Ontario L1S 2G8, Canada,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
26th Replacement of Hard Chrome and Cadmium Plating Program Review Meeting, January 24-26, 2006, San Diego, CA. Sponsored by SERDP/ESTCP.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**28**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Project Objectives

- Deeper & clear understanding of the coating performance requirements by the NAVAIR carrier based fleet with regard to:
    - Fatigue
    - Sliding Wear Resistance
    - Surface Finish
    - Corrosion Resistance
    - Interaction with Seal Materials
    - **Integrity at high stress/strain loads**
    - **Repair & Overhaul**
  - Utilize materials engineering principles to develop candidate coating solutions
  - Testing Methodology
    - To screen initial set of candidate coating systems
    - To test final selected coating system

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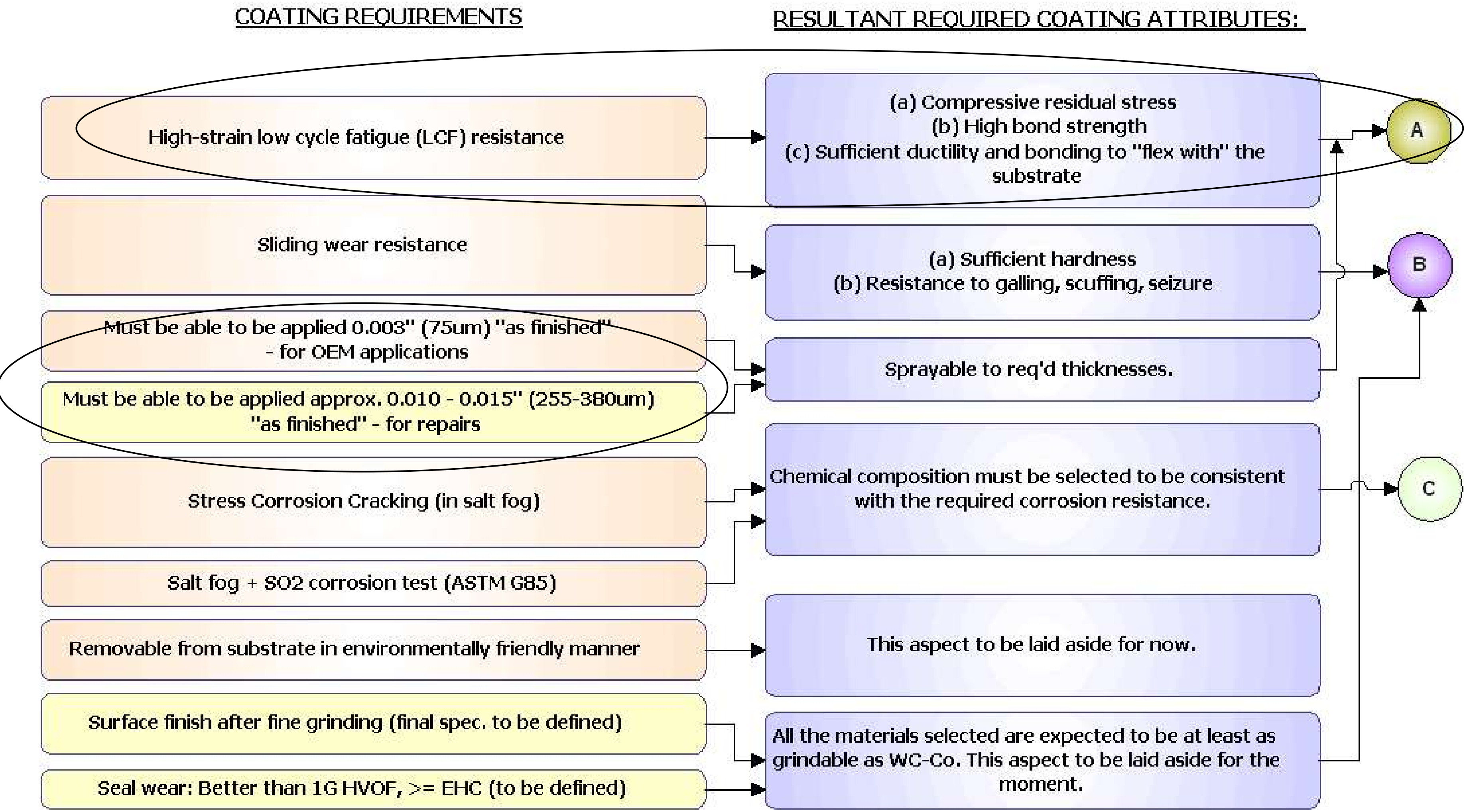
Plan to meet the NAVAIR's expectations:

- The Project concept was formed after realization from the HCAT meetings that existing coating materials will not meet NAVAIR's requirements in high load situations, such as F-18 carrier based aircraft.
- The Scope of the Project was based on detailed technical discussions between M-D and DS, and considered
  - Materials selected that will be "palatable" to the NAVAIR
  - Big bar tests. (The "key" to NAVAIR acceptability)
  - Need to prove coating material can survive the loads of big bar test
- Initial feasibility trials based on some of the materials concepts were promising

Requirements to Meet Navy's Expectations



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Requirements to Meet Navy's Expectations Con't

MATERIALS THAT CAN PROVIDE THE REQUIRED ATTRIBUTES:

A

(a) Most HVOF coatings can be sprayed with compressive residual stress and to the req'd thickness.
(b) High bond strength - higher density materials such as WC have higher bond strengths in HVOF. Hence the coating must either have a thin WC-based bond coat (thin enough to withstand the big bar test) OR it must be a composite that contains a minimum amount of carbide phase for good bonding.
(c) Ductility / resistance to cracking - implies that the main "load-bearing" part of the coating should be an alloy, OR a composite with a small amount of carbide (e.g. less than 60% by volume) OR it must contain vertical cracks, similar to hard chrome.

B

The material selected should be an alloy or combination of materials known to have **good sliding wear resistance and minimal potential for damaging counter face materials.** If a considerably softer alloy is used (compared to hard chrome or WC-Co) then work hardening properties could be advantageous.

C

Most of the Stellite and Nistelle alloys (these names are registered Trade Marks of Deloro Stellite Company Inc.) meet or exceed the corrosion requirements, and as such can be considered for the matrix or as a stand alone coating, provided the ductility is adequate.

SELECTED COATING CONCEPTS DESIGNED USING THESE ATTRIBUTES:

COATING SYSTEMS 1 & 2
(a) Sprayed with and without a **thin carbide bond coat**
(b) With **thick alloy interlayer** absorbs stresses (proprietary Ni-based and Co-based alloys).
(c) **Thin WC-17%Co or WC-10%Co-4%Cr top coat**, for wear resistance & hardness.

As sprayed

Initial Results "As sprayed"

For various reasons this concept is not practical

CONCLUSION: DISCARD SYSTEMS 1 & 2

"Post treated"

Initial Results "Post Treated"

1. Cooling rate modification during spraying was attempted. The trials were not successful (cracks could not be induced).
2. Laser surface treatment was considered. The technology is not mature enough, and holds too many challenges from a manufacturing and industrialization point of view.

CONCLUSION: DISCARD POST-PROCESSING

COATING SYSTEM 3
(a) Thin carbide bond coat for high bond strength.
(b) Wear resistant Co-based alloy top coat:
1. Good corrosion resistance in saline and complex corrosion environments, including SO2.
2. Good metal-to-metal sliding wear properties. May be work hardenable.
3. More ductile and softer than WC-based coatings (400-550HV), good sliding wear resistance.

COATING SYSTEM 4
Proprietary composite powders: corrosion resistant Co base alloy with different amounts of fine WC grains. Designed to provide the necessary balance between alloy properties (corrosion resistance, ductility, crack resistance, etc.) and WC properties (for example higher bond strength, higher hardness, proven wear resistance).

Initial Results (As Sprayed)
1. Initial results are promising
2. Material, spray parameters and powder size are being further optimized.
3. More powder for Coating System 4 cannot be manufactured before the project formally starts.
CONCLUSION: PROCEED WITH DEVELOPMENT OF SYSTEMS 3 AND 4 "as sprayed"

I. Screening tests with hydrogen fuel (DS)

26 different coating systems were sprayed on Almen strips

- Included standard powders, special distributions and unique compositions
- Included “thin” (0.004 – 0.005”) and “thick” (0.015 – 0.016”) coatings to include applications for new builds and repaired parts

– Compressive/Tensile stress of each coating was determined by measuring the deflection of the Almen strips

– Coatings were bent through 90º on a small diameter (½”) mandrel

- Coating adhesion and amount & size of cracks were determined
- Spacing between cracks an important indicator

– Assumptions were made that coatings with good adhesion and ductility will perform better in severe fatigue/high load environments

Almen Strip Data for Various Coatings

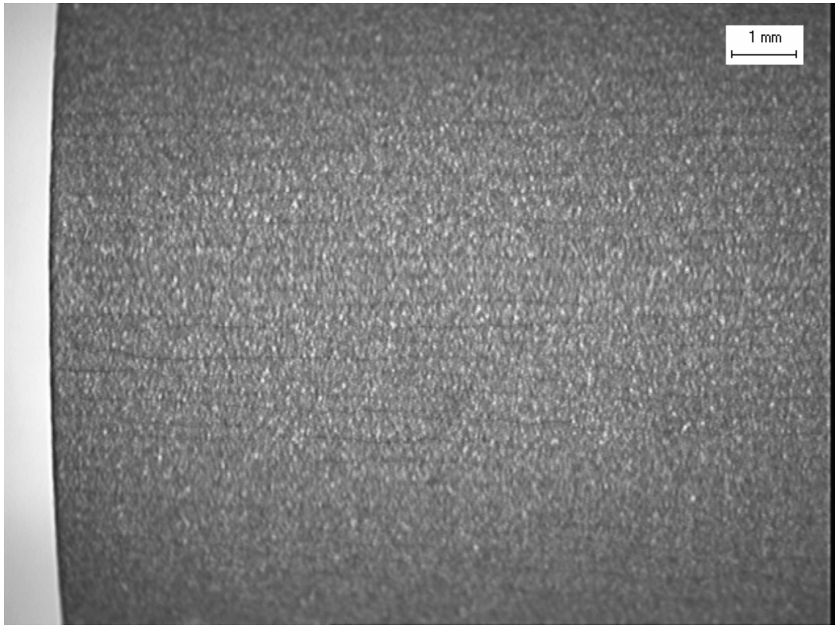
Panel ID	Deflection Mils	Thick Final	1st Layer	2nd Layer	3rd Layer
1.1	1.0-2.5 Comp.	0.005	NiCrMo	WC-CoCr	
1.3	2.0-3.5 Comp.	0.004	WC-CoCr		
1.4	6.0-11 Comp.	0.016	WC-Co	NiCrMo	WC-CoCr
1.5	3.0 Comp.-.5 Tens.	0.015	WC-CoCr		
2.1	4.0-5.5 Comp.	0.005	NiCrMo	WC-Co	
2.3	3.0-6.5 Comp.	0.005	WC-Co		
2.4	8.5-11.5 Comp.	0.017	WC-Co	NiCrMo	WC-Co
3.1	1.5-3.0 Comp.	0.004	WC-Co	CoCrMo	
3.2	4.5-7.5 Comp.	0.014	WC-Co	CoCrMo	
4.1	1.5-5.0 Comp.	0.004	WC/CoCrMo		
5.1	5.0-9.5 Comp.	0.016	WC-Co	CoCrMo	WC-CoCr
6.1	1.5-4.0 Comp	0.007	WC-CoCr	CoCrMo	
6.1 LO2	2.5 Comp-.5 Tens.	0.006	WC-CoCr	CoCrMo	
6.2	2.0-4.5 Comp	0.014	WC-CoCr	CoCrMo	
6.2 LO2	1.0-4.5 Tens.	0.016	WC-CoCr	CoCrMo	
8.1	7.0-10.0 Comp.	0.016	WC-CoCr +CoCrMo Blend		
9.1	0-1.5 Comp.	0.005	WC/CoCrMo Size 1		
9.2	-.5 to 1.0 Tens/Comp	0.005	WC/CoCrMo Size 2		
9.3	.5-1.0 Tens.	0.005	WC/CoCrMo Size 3		
9.4	0-.5 Tens	0.005	WC/CoCrMo Size4		
9.5	6.0-7.5 Comp.	0.005	WC/CoCrMo Size 1		
9.6	14.0-17.0 Comp.	0.015	WC/CoCrMo Size 1		
9.7	5.0-6.0 Comp.	0.005	WC/CoCrMo Size 3		
9.8	9.5-12.0 Comp.	0.015	WC/CoCrMo Size 3		

Screening tests - Bending

- Screening tests with hydrogen fuel Current 1st generation WC-CoCr coating (JK®120H)

0.004” total thickness

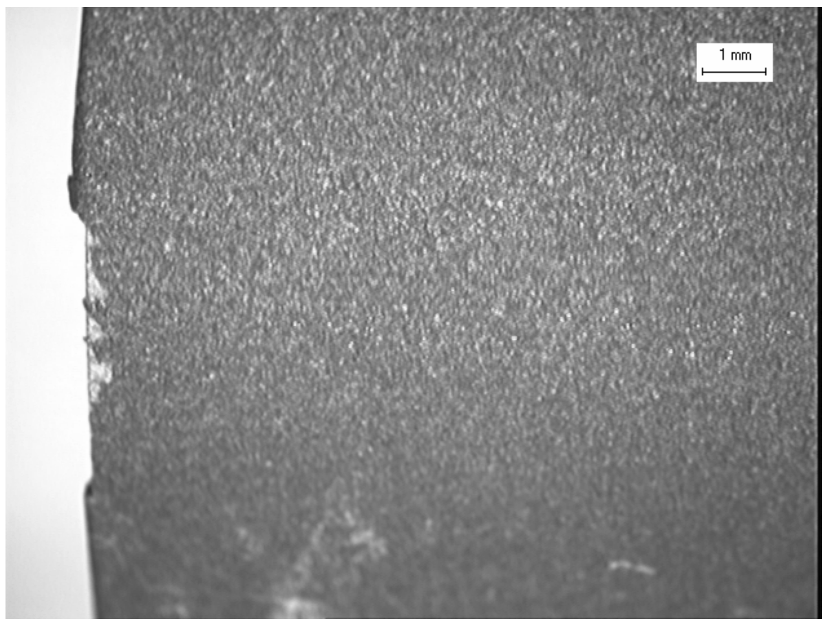
0.015”



Screening tests - Bending

- Best ranked coating in screening test (both thin & thick) was CoCrMo over WC-Co (JK®117)

0.004” total thickness 0.014”



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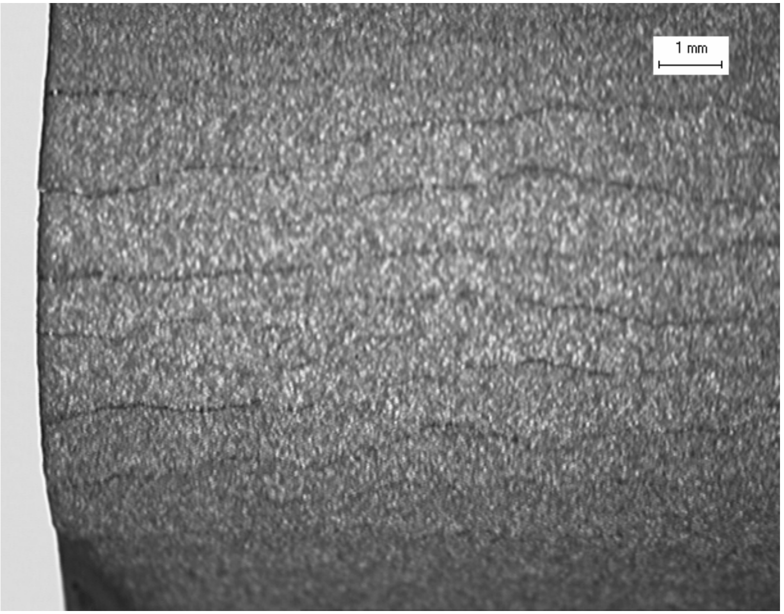
Screening tests - Bending

- New composite Alloy WC/CoCrMo performed not as good, but better than WC/CoCrMo blend

0.005" total thickness



0.015"

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Rank Based on Almen Bend Tests

Rank	Thin	Thick
1	**3.1** CoCrMo over WC-Co	**3.2** CoCrMo over WC-Co
2	**1.3** . WC-CoCr	**5.1** WC-CoCr over CoCrMo over WC-Co
3	**6.1** Low $\mathbf{O_2}$ CoCrMo over WC-CoCr	**1.4** WC-CoCr over NiCrMo over WC-Co
4	**6.1** CoCrMo over WC-CoCr	**2.4** WC-Co over NiCrMo over WC-Co
5	**9.7** WC/CoCrMo Size 3	**9.8** WC/CoCrMo Size 3
6	**9.3** WC/CoCrMo Size 3	**9.6** WC/CoCrMo Size 1
7	**9.4** WC/CoCrMo Size 4	**8.1** WC-CoCr +CoCrMo Blend
8	**4.1** WC/CoCrMo	**6.2** CoCrMo over WC-CoCr
9	**9.5** WC/CoCrMo Size 1	**1.5** WC-CoCr
10	**9.2** WC/CoCrMo Size 2	**6.2** Low $\mathbf{O_2}$ CoCrMo over WC-CoCr
11	**9.1** WC/CoCrMo Size 1	
12	**2.3** WC-Co	
13	**1.1** WC-CoCr over NiCrMo	
14	**2.1** WC-Co over NiCrMo	

Lessons Learned from Bend Specimens

- Coating thickness a significant role in degree of cracking
  - Best thick coating is visually similar to worst thin coating
- WC-CoCr (JK®120H) do not have as high of cohesive strength as WC-Co (JK ®117) when used as a bond coat
- Mechanical alloy and blend of CoCrMo and WC produced good coatings with higher compression than standard powders
  - However the coatings did not provide adequate bond at 0.016” thickness to be considered for the thick overlay needed for repairs.

- For thick coatings, multi-layered performed better than single layer coatings.

Ranking Overall

- Coating Compressive Stress Ranking
  - Composite > Blended > Coatings in Multiple Layers

- Coating Bonding/cracking Resistance Ranking
  - Coatings in Multiple Layers >Composite = Blended

- WC-Co as “bond coat” with CoCrMo top coat better bond strength than WC-CoCr

- Although main objective is a single layer coating with high compression, and adequate bond strength for thick coatings, multilayer coatings appear to perform better from bend tests

II. Small Bar Fatigue Tests

- Three coating systems were selected for small bar fatigue tests
  - 2 layered coating: CoCrMo top coat over WC-Co bond coat
  - 3 layered coating: WC-CoCr top coat, CoCrMo interlayer, WC-Co bond coat
  - 1 layer coating: WC/CoCrMo composite
- Thick and Thin Coatings were tested in ground polished condition
- Test conditions:
  - Material: Shot Peened 4340 (260-280 with yield ~220ksi)
  - Test specification: ASTM E-466-96
  - 32 Ra finish
  - Load 220KSI, R= -1
  - Test temperature 75^{o}F

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Small Bar Fatigue Tests Results

- Thin coatings ran until failure of metal bar
- Thick coatings showed early coating cracking prior to spalling or failure of bar

ID	Coating Material	Thickness	Cycles	Failure
103	CoCrMo over WC-Co	.004”	664	Bar failure at edge of patch
104	CoCrMo over WC-Co	.004”	669	Bar failure at edge of patch
105	CoCrMo over WC-Co	.012”	25	Severe Cracking
106	CoCrMo over WC-Co	.012”	64	Crack on startup spalled
107	WC-CoCr Over CoCrMo over WC-Co	.012”	43	Severe Cracking
108	WC-CoCr Over CoCrMo over WC-Co	.012”	90	Longitudinal Crack
109	WC-CoCr Over CoCrMo over WC-Co	.004”	566	Coating Spalled in Bands
110	WC-CoCr Over CoCrMo over WC-Co	.004”	617	Bar failure at edge of patch
111	WC/CoCrMo	.004	90	Cracked and spalled
112	WC/CoCrMo	.004	148	Spalled
113	WC/CoCrMo over Wc-co	.012	50	Spalled
114	WC/CoCrMo over Wc-co	.012	65	Spalled

Small Bar Fatigue Tests (Thin Coatings)

- CoCrMo over WC-Co
- Thin coatings, ran till bar failure

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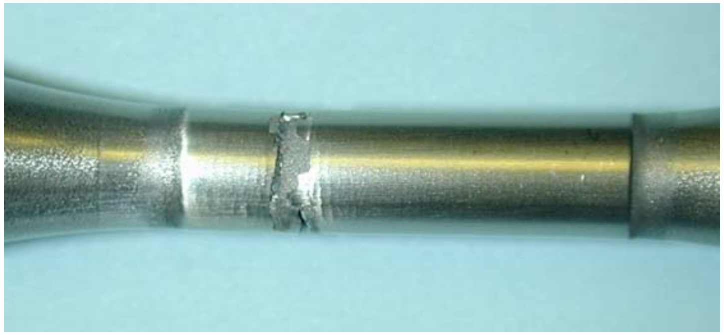

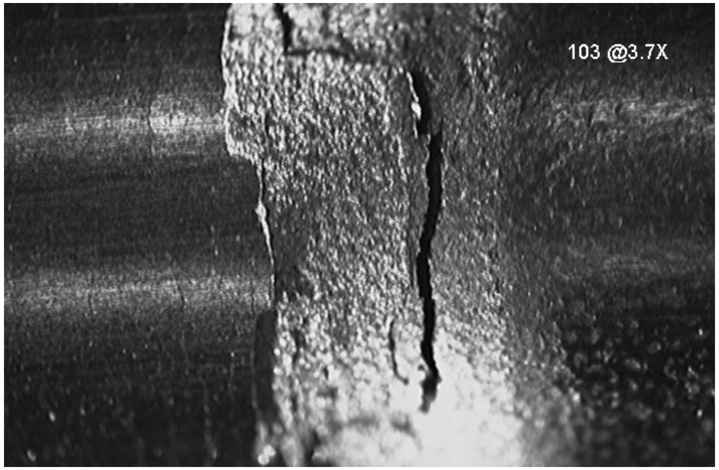

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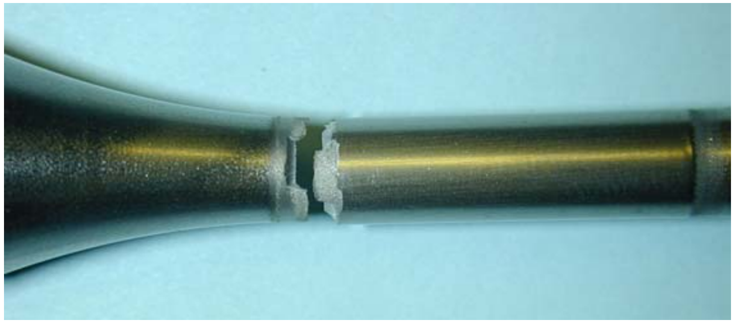
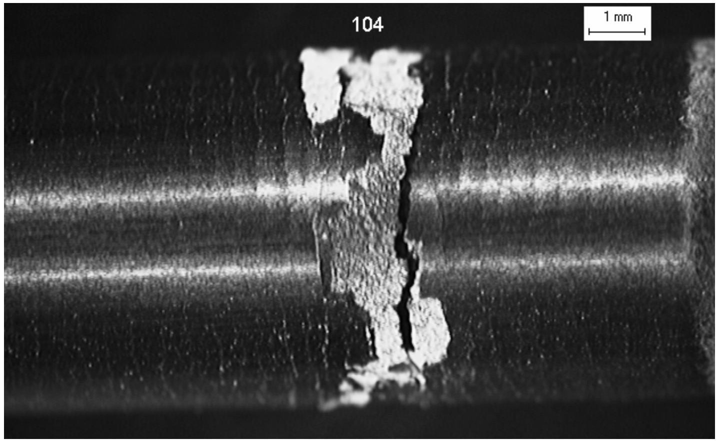
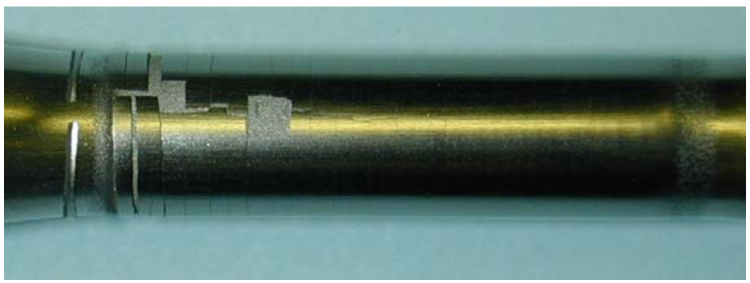


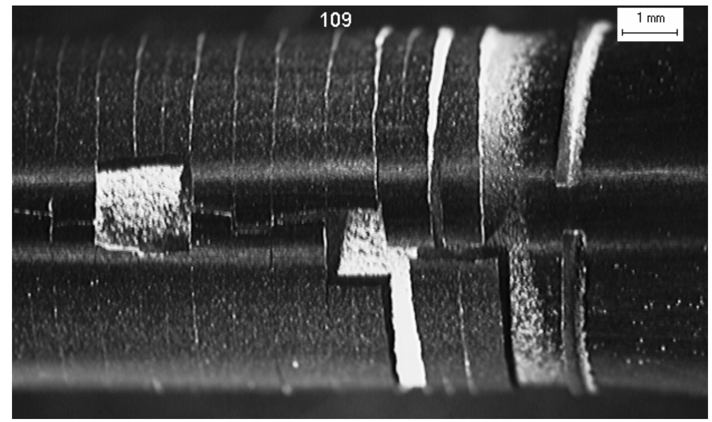


Small Bar Fatigue Tests Thin Coatings

- WC-CoCr over CoCrMo over WC-Coat
- Thin coatings, ran till bar failure

109





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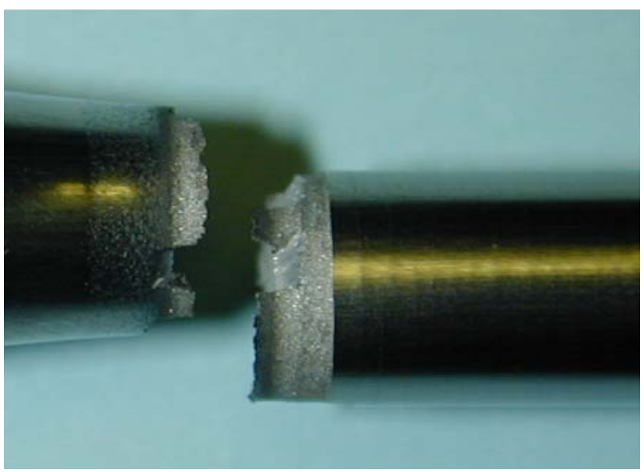
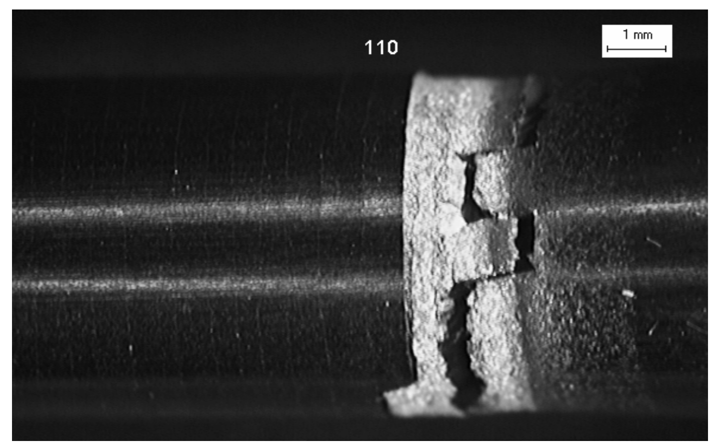
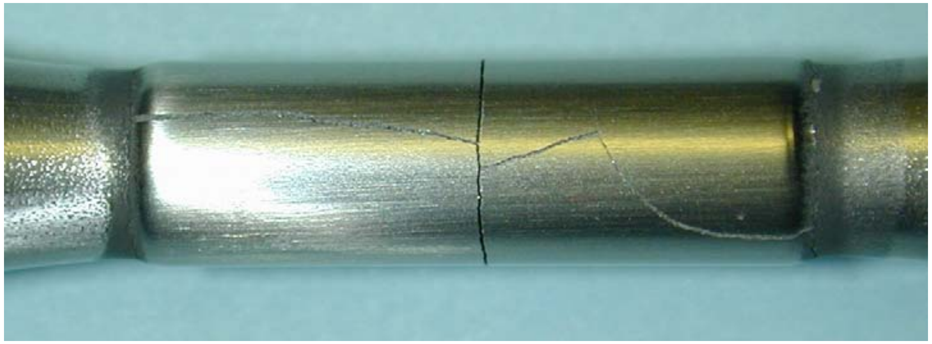




Small Bar Fatigue Tests (Thick Coatings)

- Thick coatings failed early due to coating cracking
- CoCrMo over WC-Co — sample 105
- WC-CoCr over CoCrMo over WC-Co — sample 107

105



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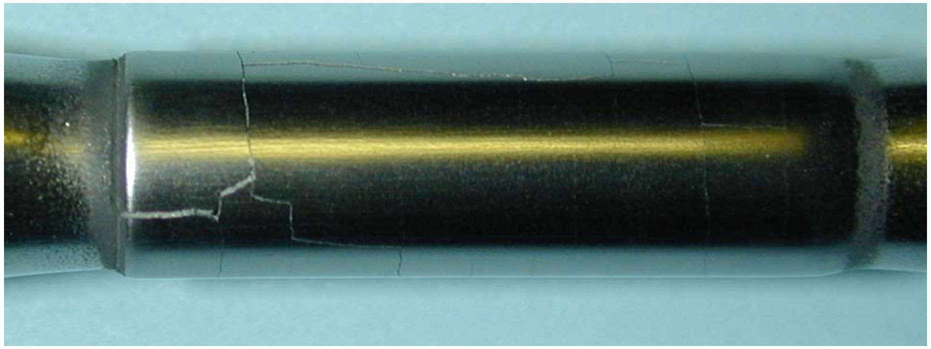

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Small Bar Fatigue Tests

- "Thin" coatings exhibited very good adhesion to substrate, even adhesion at fracture surface
- Difficult to select best "thin" coating, but it appears that 3-layered coating is more variable (need to be confirmed)
- Results were promising enough to perform the big bar test with some optimization

Methane Produced Coatings

- **Developed natural gas parameters (MD & DS)**
  - **Equivalency tests between H_2 and Methane gas (MD)**
  - **MD received initial spray parameters from Stellite**
  - **MD performed some optimization to increase compression**
  - **Spray big bars**
  - **Test at Metcut using Navair test criteria**

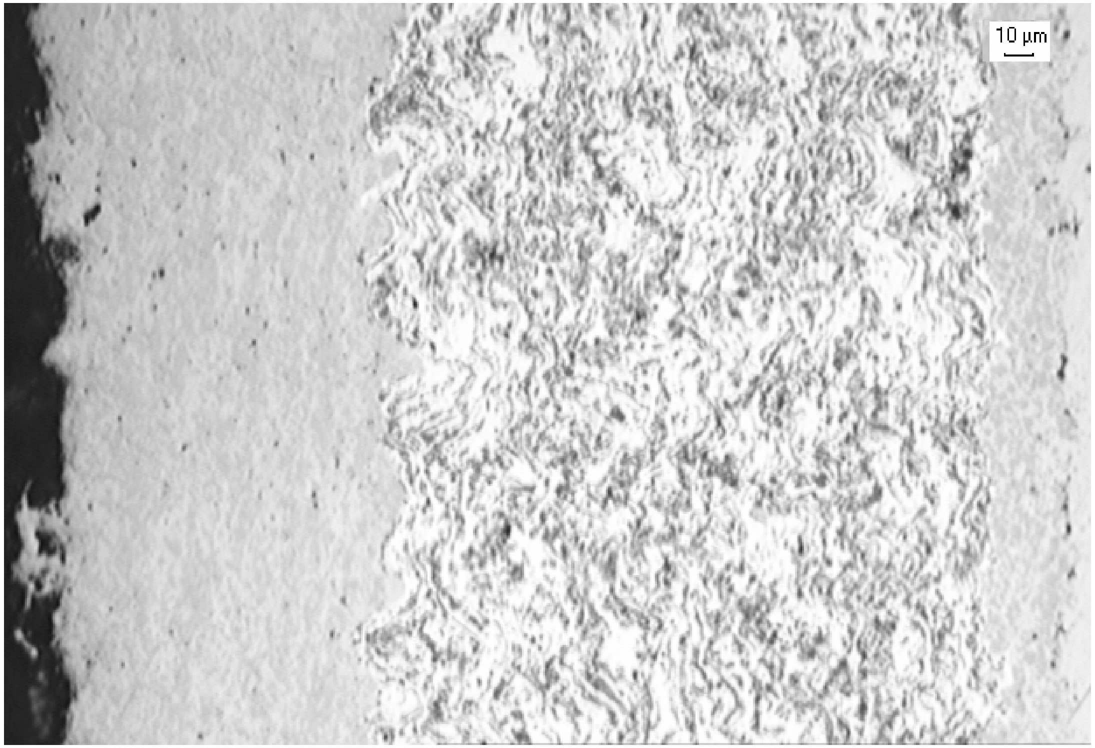
III. Coatings for Big Bar Test

- Three potential coating systems were selected after screening tests
  - WCCoCr over CoCrMo over WCCo via hydrogen fuel at Stellite Coatings
  - WCCoCr over CoCrMo over WCCo via Methane fuel at Messier-Dowty, Ajax
  - CoCrMo over WCCo via Methane fuel at Messier-Dowty, Ajax
- 1st generation coating, WCCoCr used as a reference coating
- All coatings were applied to finish at .015” thick

Deloro Stellite Coating on Big Bar

- **WCCoCr over CoCrMo over WCCo Via Hydrogen Fuel using Jet Kote®**
- **Coating thickness Total about .017”**

Bend Specimen



Coating cross-section @ 200X

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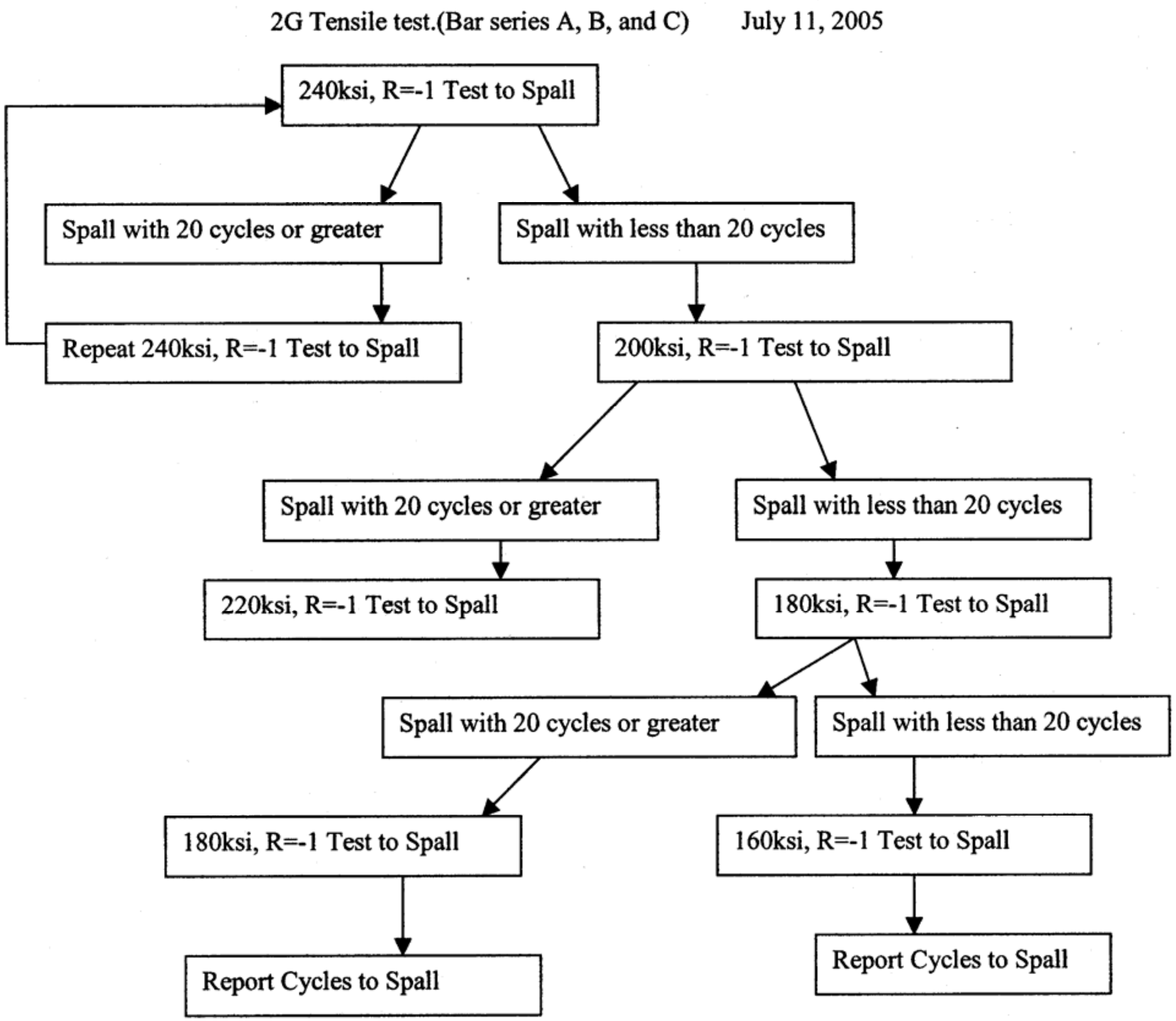
Test Approach



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Test Results

Table I
Cyclic Fatigue Data
300M steel
3.25-12 hollow smooth gage

Stress Ratio : R = -1.0 | Frequency : 1 Hz
Test Temperature : 75 °F | Waveform : Sinusoidal

Project No. : 3945-82063-21-265-01-01

Test Number	Specimen Number	Outside Diameter * (in)	Inside Diameter (in)	Stress Max (ksi)	Cycles	Actual Frequency (Hz)	Results	Test Hours	Test Machine
1-265	A-1 (1)	2.2498	1.9974	228 (240)	1	0.25	coating spall	0.1	60085
4-265	A-2 (2)	2.2500	1.9980	200	63	0.25	coating spall	0.1	60085
9-265	A-3 (3)	2.2504	2.0002	220	16	0.25	coating spall	0.1	60085
10-265	A-4 (4)	2.2462	1.9982	200	8	0.25	coating spall	0.1	60085
2-265	B-1 (5)	2.2485	1.9980	240	40	0.25	coating spall	0.1	60085
5-265	B-2 (6)	2.2500	1.9982	240	62	0.25	coating spall	0.1	60085
7-265	B-3 (7)	2.2505	1.9970	240	54	0.25	coating spall	0.1	60085
3-265	C-1 (8)	2.2490	1.9974	240	30	0.25	coating spall	0.1	60085
6-265	C-2 (9)	2.2520	1.9982	240	33	0.25	coating spall	0.1	60085
8-265	C-3 (10)	2.3564	2.1068	240	79	0.25	coating spall	0.1	60085

* Uncoated dimension

Samples A-1 to A-4

WC-CoCr

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Samples B-1 to B-3

CoCrMo over WC-Co

Samples C-1 to C-3 WC-CoCr over CoCrMo over WC-Co

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Conclusions

- Big bar results indicate coatings developed and screened in the body of this work may met the needs suggested by NAVAIR regarding high stress loads
- Material engineering exercise proved useful in developing better coatings to withstand high stress loads.
- We feel confident further improvement in performance can be achieved.
- Talks have begun with A380 design team regarding repair schemes

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