High-Strength Steel Joint Test Protocol For Validation of Alternatives to Low Hydrogen Embrittlement Cadmium For High-Strength Steel Landing Gear and Component Applications

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The goal of the Joint Test Protocol (JTP) is to establish a single suite of performance requirements to qualify new materials and processes as acceptable replacements for low hydrogen embrittlement cadmium (LHE-Cd) for the user community, including both the Department of Defense (DoD) and industry. Also, it is intended that the requirements will guide the development of new materials and procedures that could have the potential to replace LHE-Cd. The JTP captures the performance requirements and test procedures for coatings applied to existing high strength steel structures on which LHE-Cd and ion vapor deposited aluminum (IVD-Al) are now used. These coatings principally provide corrosion protection, paint adhesion to the component, and a compatible galvanic couple between the steel and other metallic materials in the assembly, including bronze bushings, stainless steel pins and fasteners, and aluminum components. The JTP defines methods to evaluate these attributes as well as hydrogen embrittlement and re-embrittlement and metal fatigue characteristics that might impact current component design.

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BACKGROUND AND OBJECTIVE

The Department of Defense (DoD) conducts cadmium electroplating for a number of applications, which include coating weapon system components and assemblies that are constructed from a variety of metal substrates. Cadmium coatings impart physical properties to meet mission performance requirements such as galvanic and sacrificial corrosion protection, lubricity, acceptance of conversion coating for paint adhesion, torque-tension for threaded applications, and galling prevention. Further, cadmium plating is an inexpensive process to operate and maintain. While cadmium is desirable from a performance and cost standpoint, it does possess some shortcomings. Namely, cadmium is a carcinogen and toxic substance that produces waste streams that are detrimental to the environment. For these reasons, Federal, state, and local compliance agencies strictly control the use and disposal of cadmium. Additionally, health and safety standards have lowered worker permissible exposure limits, which have resulted in excessive in-service costs. Due to cadmium's toxic nature, additional regulations are evolving that will mandate the reduction, and possibly the elimination, of cadmium. Therefore, the DoD must identify and validate cadmium alternatives before such regulations are instituted.

To address this need, the U.S. Air Force Research Laboratory (AFRL) contracted Concurrent Technologies Corporation (*CTC*), in cooperation with The Boeing Company (Boeing), to develop a Joint Test Protocol (JTP) that can be used to evaluate potential cadmium plating alternatives. The JTP that *CTC* and Boeing have been asked to design is focused on high-strength steel (HSS) applications, specifically landing gear components. This task is a DoD-wide initiative, and to support its development and ensure accuracy and effectiveness, input from the joint service community (Air Force, Army, and Navy), as well as original equipment manufacturers (OEMs), is a necessity. The goal of the JTP is to design and outline a single suite of performance requirements and test methods that can be used to fully assess the fundamental capabilities of alternative processes. The JTP will, in essence, provide a means of confirming vendor performance claims, allow for joint service analyses, and outline requirements for coating developers to qualify new materials and processes to replace cadmium.

PROJECT BACKGROUND

To ensure that the JTP accounted for all aspects of landing gear plating activities, *CTC* sought the participation of Boeing to provide technical support for this effort. Boeing was selected based on their previous experiences related to JTP development[1] and extensive cadmium

[1] Past Boeing JTP development includes: The Joint Group for Pollution Prevention (JG-PP) task entitled "Alternatives to Electrodeposited Cadmium for Corrosion Protection and Threaded Part Lubricity Applications," BISDS project; National Defense Center for Environmental Excellence (NDCEE) Mission Demonstration 7 entitled "Alloy Plating to Replace Cadmium on High Strength Steels."

alternative investigations. They bring direct experience to the table as well as manufacturing considerations.

Before the JTP was developed to its present state, an initial test protocol was prepared to delineate and describe the performance requirements for coatings that are applied to HSS structural alloy steel (>200 ksi) landing gear components, as processed by Hill Air Force Base (AFB)/Ogden Air Logistics Center (OO-ALC). This initial test protocol also was a collaborative effort between *CTC* and Boeing. Specifically, *CTC* assisted Boeing in the establishment of the team, which included representatives from Boeing-St. Louis, Boeing-Mesa, Air Force Materiel Command (AFMC), AFRL, Hill AFB/OO-ALC, and *CTC*.

Boeing designed an outline for the initial test protocol based on the performance requirements listed within FED-STD-QQ-P-416 and MIL-STD-807B. These items were combined with input that had been gathered from the team and direct feedback from Hill AFB/OO-ALC personnel that focused on additional requirements not specifically called out within the specifications and current cadmium plating practices. Once completed, the outline was presented to the Hill AFB/OO-ALC landing gear experts. Upon its presentation, the initial test protocol outline was reviewed and it was determined that a distinction needed to be made between performance requirements and additional testing (i.e., testing based on commercial practice or inputs from individuals experienced in dealing with high strength steel applications).

Per AFRL direction, the test protocol was expanded to cover the joint services and therefore, required input from the Army and Navy, in addition to, OEMs. To properly acknowledge the joint focus of the test protocol, the document was renamed the JTP. Further, a formal team consisting of representatives from the original Joint Cadmium Alternatives Team (JCAT) as well as some new representatives from all of the DoD services, the OEM community, and *CTC* was formed. This reformed team kept the name of JCAT..

JOINT TEST PROTOCOL

The performance requirements and test procedures described within the JTP focus on the requirements for coatings applied to existing HSS structural components where low hydrogen embrittlement cadmium (LHE-Cd) or ion vapor deposited aluminum (IVD-Al) are now used. LHE-Cd and IVD-AL principally provide corrosion protection, paint adhesion to the alloy steel landing gear structure, and a compatible galvanic couple between the alloy steel and other metallic materials in the assembly including bronze bushings, stainless steel pins and fasteners, and aluminum components. However, these coatings do have issues related to their use. Specifically, the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) strictly control the use and disposal of LHE-Cd because of cadmium's toxic nature. Even though aluminum is not considered a detrimental material , IVD-Al is a dimensionally-limited process. At the present time, it cannot treat components that have deep recesses or blind holes as are common to many landing gear components; therefore, it does not completely eliminate the use of cadmium.

The JTP defines methods to evaluate alternatives' properties and capabilities to replace LHE-Cd. In addition to the above-mentioned characteristics, the JTP addresses hydrogen embrittlement and metal fatigue characteristics that might impact current HSS designs. The JTP defines all test requirements as agreed upon by the JCAT, which states that an alternative process must exhibit performance that is equal to or exceeds that of cadmium to be considered a viable replacement for HSS applications. For each testing requirement, the JTP details the following information:

- Test descriptions including test parameters and conditions, test specimens/substrates, number of trials, and acceptance criteria
- Test rationales
- Test methodologies
- Equipment or instrumentation details related to the testing
- Data analysis section for those tests where the recorded data are to be manipulated prior to analysis.

Table 1 lists the performance requirements included within the JTP, along with the test specimen size, shape, material of construction, and number of specimens per alternative. The JTP requires that all of the candidate coatings be applied per manufacturers' instructions or specification requirements, if available. The application process, including thickness, supplemental coatings, post plate baking, etc., is required to be completed in accordance with production methods as outlined by the vendors. Per JCAT decision, specimens are not to be peened prior to plating because unpeened specimens will better highlight the fatigue effects.

In addition to the engineering requirements listed in Table 1, the JTP includes supplementary sections to incorporate any further testing or alternative acceptance criteria that may be required by the individual services (Air Force, Army, or Navy) that is above and beyond the JTP. Table 2 summarizes those tests by service.

The JTP also takes into account further testing that may be required prior to implementation of a viable alternative coating. The JCAT included a recommendation section in the JTP that lists the supplementary tests, which include variations of adhesion testing, fatigue testing, and hydrogen re-embrittlement.

Table 1. JTP Engineering and Performance Test Matrix

Test Category	Test	Test Method	Size of Specimen and Substrate	Number of Specimen per Alternative
General Properties	Appearance	Visual	4" x 6" x 0.04"; AISI 4130 *	3
	Throwing power and Alloy composition uniformity	Tube fixture	4" x 6" x 0.04"; AISI 4130	3
	Stripability	Manufacturer recommendation or MIL-S-5002D	1" x 4" x 0.04"; AISI 4130	3
		Hydrogen embrittlement per ASTM F519	Type 1a.1; AISI 4340	8
	Galvanic potential	Electrochemical analysis	4" x 6" x 0.04" ;AISI 4130	2
Adhesion	Bend adhesion	Vise/bend to break	1" x 4" x 0.04"; AISI 4130, 17-4PH, Ti6Al4V	5 per substrate
	Paint adhesion	Tape adhesion, ASTM D 3359	4" x 6" x 0.04"; AISI 4130	27
Corrosion	Unscribed neutral salt fog (NSS) (bare)	3,000 hrs, ASTM B 117	4" x 6" x 0.04"; AISI 4130	3
	Scribed NSS (bare)	1,000 hrs, ASTM B 117	4" x 6" x 0.04"; AISI 4130	3
	Galvanic corrosion resistance	168 hrs, ASTM B 117 336 hrs, ASTM G 85 Annex 5	1" washers; AISI 4130, 17-4PH, CuBe, AlNiBr AMS 4640	12 per substrate
	Fluid corrosion resistance	ASTM F 483	1" x 2" x 0.032"; AISI 4130	41
	Scribed w/ primer & topcoat	3,000 hrs, ASTM D 1654	4" x 6" x 0.04"; AISI 4130	9
Lubricity	Run-on/Break-away torque	MIL-STD-1312	Specified nuts and bolts; Specified alloy steel	20
	Torque-tension	MIL-STD-1312	Specified nuts, bolts and washers; Specified alloy steel	10 of each specified substrate
Fatigue	Rotating beam fatigue	RR Moore, smooth & notch	Smooth and notched RR Moore specimens; 300M **	18 of each type
Hydrogen Embrittlement & Re-embrittlement	Notch tensile – as coated	ASTM F519	Type 1a.1 notched round bars; AISI 4340 ***	4
	Incremental Step Load (ISL) procedure while immersed in fluid	ASTM F 1624	Type 1a.1 notched round bars; AISI 4340	12
Reparability	Appearance	Visual	4" x 6" x 0.04"; AISI 4130	1
	Bend adhesion	On 4130	1" x 4" x 0.04"; AISI 4130	3
	Paint adhesion	Tape adhesion, ASTM D 3359	4" x 6" x 0.04"; AISI 4130	9
	Unscribed corrosion resistance	3,000 hrs, ASTM B 117	4" x 6" x 0.04"; AISI 4130	3
	Scribed corrosion resistance	1,000 hrs, ASTM B 117	4" x 6" x 0.04"; AISI 4130	3
	Hydrogen embrittlement	ASTM F 519	Type 1a.1; AISI 4340	4

* For cost control, alloy AISI 4130 conforming to AMS 6350, low-strength steel, is used for adhesion and corrosion tests and for general properties determination.
** Fatigue tests are a specialized specimen shape to be made of 300M conforming to AMS 6419
*** Hydrogen embrittlement and re-embrittlement tests use specialized coupons made of AISI 4340 conforming to AMS 6414.

Table 2. Additional Test Requirements

DoD Service	Test Category	Test	Comments
Navy	Corrosion	Unscribed cyclic SO_2 salt spray	Follow ASTM G85 Annex 4
		Scribed cyclic SO_2 salt spray	
		Cyclic SO_2 salt spray of scribed painted coatings	
		Corrosion fatigue test	Test per Navy direction
		Stress corrosion cracking	Test per Navy direction
	Lubricity	Run-on and breakaway torque	Add a corrosion step to the specified testing
	Fatigue	Rotating beam fatigue	May require testing a second geometry at additional axial fatigues
Air Force	Lubricity	Torque tension test	Adjustment of acceptance criterion
Army	Hydrogen Embrittlement & Re-embrittlement	AMCON in-service hydrogen re-embrittlement/stress corrosion cracking test	Test per ASTM F519 and GM 9540P

FUTURE ACTIVITIES

It was decided that the testing contained within the JTP would be completed through a series of iterative phases. The JCAT agreed upon a three-phased approach. Phase I will consist of hydrogen embrittlement and re-embrittlement testing, including the AMCOM In-Service Hydrogen Re-Embrittlement/Stress Corrosion Cracking C-Ring Test. The results from Phase I will be compiled and reviewed by the JCAT to determine which alternatives will be evaluated in Phases II and III. Phase II consists of the majority of the JTP tests, with the addition of the Navy requested sulfur dioxide (SO_2) salt fog testing. Finally, Phase III work will evaluate fatigue testing, which is the most expensive test outlined in the JTP. For this reason, it is intended that only the most promising alternatives will pass on to Phase III. Table 3 identifies, by test phase, the test category, individual tests, and proposed testing facility.

Table 3. JTP Testing Facility

Test Category	Test	Proposed Testing Facility
PHASE I TESTING		
Hydrogen Embrittlement & Re-embrittlement	Hydrogen embrittlement - notched bar	NAVAIR**
	Hydrogen re-embrittlement – ISL notched bar	NAVAIR
	AMCOM C-Ring Test *	ARL***
PHASE II TESTING		
General Properties	Appearance	*CTC*
	Throwing power and Alloy composition uniformity	Boeing
	Stripability	NAVAIR
	Galvanic potential	Boeing
Adhesion	Bend adhesion	NAVAIR
	Paint adhesion	NAVAIR
Corrosion	Unscribed NSS (bare)	ARL
	Scribed NSS (bare)	ARL
	Galvanic corrosion resistance	Boeing
	Fluid corrosion resistance	Boeing
	Scribed w/ primer & topcoat	NAVAIR (paint) / ARL (test)
	SO2 Salt Fog *	NAVAIR
Lubricity	Run-on/Break-away torque	Boeing
	Torque-tension	Boeing
Reparability	Appearance	Boeing
	Bend adhesion	Boeing
	Paint adhesion	Boeing
	Unscribed corrosion resistance	Boeing
	Scribed corrosion resistance	Boeing
	Rotating beam fatigue	Boeing
	Hydrogen embrittlement	Boeing
PHASE III TESTING		
Fatigue	Rotating beam fatigue – smooth bar	Boeing
	Rotating beam fatigue – notched bar	Boeing

* Additional tests agreed upon by the JCAT.
** NAVAIR = Naval Aviation Center.
*** ARL = Army Research Laboratory.

Per a JCAT decision, *CTC* will coordinate all of the testing activities associated with the JTP. The AFRL and the Environmental Security Technology Certification Program (ESTCP) will provide test support. Because the goal of the JCAT is to actively involve DoD facilities with the execution of the JTP, the primary contacts for processing and testing are the DoD facilities.

The JCAT also prioritized potential alternatives to include in the execution of the JTP. Table 4 lists the alternatives that were selected by the JCAT for evaluation during Phase I of testing, in addition to the name of the vendor or DoD facility that will apply the coating(s).

Table 4. Cadmium Alternatives for JTP Testing

Alternative	Proposed Vendor/DoD Facility
LHE Cadmium (control)	Hill AFB
IVD Aluminum (control)	Hill AFB
Aluminum Manganese	NAVAIR
Electroplated Aluminum	Vendor A
Sputtered Aluminum	Hill AFB
Zinc-Nickel, acid	Boeing
Tin-Zinc	Vendor B*
LHE Cadmium – brush repair (control)	TBD **
Aluminum-Ceramic Repair Coating	Vendor C *
Zinc-Nickel, alkaline – brush repair	Vendor D *

* The appropriate vendor will be contracted to apply the alternative coating.
** TBD = to be determined.

STATUS

At the time this paper was developed, the DoD facilities and vendors listed in Table 3 were contacted to gather cost estimates, schedules, and commitments. No processing or testing activities were yet initiated.

SUMMARY

CTC and Boeing, working in cooperation with representatives from the Air Force, Army, Navy, and other OEMs, has designed a JTP that will be used to evaluate potential alternatives for cadmium electroplating of HSS. To meet this goal, the JCAT was reconvened and worked together to finalize the JTP and select viable candidate processes for testing and evaluation. They have agreed to review data and recommend and support implementation activities (pending positive test results). At present time, only planning work has been completed. Actual processing and testing activities have not been initiated. It is anticipated that Phase I testing efforts will be started by early 2004.

For additional information related to the JTP, test results, and independent studies, visit the Joint Group for Pollution Prevention (JG-PP) website at http://www.jgpp.com/projects/projects_index.html and select the "Joint Cadmium Alternatives Team" link.

REFERENCES

Final Report, "Task 35M - High-Strength Steel Test Protocol", Task Order 5TS5702D035M, Concurrent Technologies Corporation (31 July, 2003).

Test Protocol, "Task 35M - High-Strength Steel Joint Test Protocol for Validation of Alternatives to Low Hydrogen Embrittlement Cadmium For High-Strength Steel Landing Gear and Component Applications", Task Order 5TS5702D035M, Concurrent Technologies Corporation (31 July, 2003).