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TEST REPORT – DIRECT PART MARK TEST PROGRAM
DIRECT PART MARK SURVIVABILITY TEST PROGRAM
FOR
NORMAL AIRCRAFT LANDING GEAR PART OVERHAUL CONDITIONS

PREPARED

FOR

OO-ALC/LGHEL

BY

AGING LANDING GEAR LIFE

EXTENSION PROGRAM

PREPARED UNDER

CONTRACT GS-23F-0150L

FOR OGDEN AIR LOGISTICS CENTER

HILL AFB, UTAH

PROJECT 39135

GENERAL ATOMICS

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SIGNATURE PAGE

TEST REPORT – DIRECT PART MARK TEST PROGRAM DIRECT PART MARK SURVIVABILITY EVALUATION FOR NORMAL AIRCRAFT LANDING GEAR PART OVERHAUL CONDITIONS

PREPARED
FOR
OO-ALC/LGHEL

BY

AGING LANDING GEAR LIFE EXTENSION PROGRAM

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INTRODUCTION

Under the Aging Landing Gear Life Extension (ALGLE) Program, a test program was conducted to evaluate the survivability of machine readable marks applied with direct part marking (DPM) processes for normal aircraft landing gear part overhaul conditions. OO-ALC/LGHEL is working to qualify DPM processes and machine readable marks for marking recoverable landing gear parts. The test program was to determine if the machine readable marks provide lifetime traceability for landing gear parts by surviving normal aircraft landing gear part overhaul conditions.

For the test program, several guidelines were considered. The primary guidelines were: the mark(s) and reader(s) must provide lifetime traceability for landing gear parts; and the mark(s) and reader(s) must function as an automatic identification and tracking technology to assist an operator in collecting data directly from landing gear parts in an overhaul environment.

The secondary guidelines were: the test program should focus on finding robust marks that survive an overhaul environment with minimum overhaul process controls or no overhaul process controls; if marks are damaged, the test program should focus on identifying the overhaul processes that damaged the mark(s) and then identifying appropriate overhaul process controls to maintain the mark(s); and if possible the test program should focus on finding a single optimum mark for landing gear parts.

The tertiary guidelines were: the mark(s) and reader(s) should compete with increased traceability and efficiency with existing marking practices. The current DPM processes for landing gear parts include vibropeening and impression stamping human readable marks. Overhaul process work control documents, ink stamping, and labels are also used to track landing gear parts, but were not directly considered because they are not permanent marking methods. Considerations were given to traceability improvements over the existing DPM processes of vibropeening and steel stamping. However, since initially no problems were reported for the existing DPM processes, it was a tertiary consideration.

The test program was a research and development effort. Before the test program was conducted, research into existing documents uncovered no test reports on the survivability of machine readable marks in aggressive environments. However, the research indicated that machine readable marks applied with DPM processes were the only automatic identification and tracking technologies that had the potential to survive aggressive environments such as landing gear overhaul environments and provide lifetime traceability. The test program used marks on coupons and focused on processing the coupons as though the marks were applied to the marking surfaces of a landing gear part. If robust marks or an optimum mark were found, then more detailed testing could be conducted to include more materials, more surfaces, more topographies, multiple overhaul conditions, and condemned landing gear parts.

The test program did not consider the full complexity of adapting a serial number tracking system based on machine readable marks. Implementation considerations include developing DPM process specifications, developing standard mark data content, identifying the mark locations for each part, addressing whether the mark location would require a drawing revision or whether the mark location would be incorporated into secondary documentation such as technical orders. The test program did not consider mark repairability, since the marks are intended to provide lifetime traceability and become a permanent feature of a part. The test program did not conduct any mark and material characterization to investigate degrading effects of the marks on the material. The test program did consider return on investment analysis. The test program did not consider the full complexity of adapting a serial number tracking system based on machine readable marks, but the test program was a necessary requirement to review the technology and to provide a data package to assist in the decision making processes.

OBJECTIVES

The objective was to evaluate the survivability of marks applied with DPM processes for normal aircraft landing gear part overhaul conditions. The objective was to identify specific overhaul processes that the marks survive, and specific overhaul processes that damage the marks.

The objective was to find robust marks that survive an overhaul environment with minimum overhaul process controls or no overhaul process controls. If marks were damaged, the objective was to identify the overhaul processes that damaged the marks and then identify appropriate overhaul process controls to maintain the mark.

If possible, the objective was to find a single optimum mark for steel and aluminum landing gear parts.

TEST MATRIX AND DISCUSSION

Test Matrix

Symbol

Data Matrix™

Data

40 Alphanumeric Characters: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

(Representative Mark, Not to Scale)

20 Alphanumeric Characters: XXXXXXXXXXXXXXXXXXXX

(Representative Mark, Not to Scale)

DPM Processes

Dot Peen
LaserShot™ Peen
Micro-Mill
Laser Bond
Laser Etch
Gas Assisted Laser Etch (GALE)
Laser Engrave
Laser Induced Surface Improvement (LISI)
Vibropeen (Not a Machine Readable Mark)
Impression Stamp / Steel Stamp (Not a Machine Readable Mark)

Materials

Steel, 4340, 260ksi UTS, Marked After Heat Treat
Steel, 4340, 260ksi UTS, Marked Before Heat Treat
Aluminum, 7075-T73, 60ksi UTS

Surfaces

Marking Surface
Flat Surface

Topographies

Smooth Surface, 125RMS

Overhaul Processes

Specification	Description
AMS-H-6875	Heat Treatment of Steel
ASTM-E-1444	Fluorescent Magnetic Particle Inspection
ASTM-E-1417	Fluorescent Penetrant Inspection
MIL-STD-7179	Finishes, Coatings, and Sealants for the Protection of Aerospace Weapons Systems
MIL-P-85582	Primer Coatings, Epoxy, Waterborne
MIL-C-85285	Coating, Polyurethane, High-Solids
MIL-STD-871	Electro-Chemical Stripping of Inorganic Coatings
MIL-STD-1504	Abrasive Blasting
MIL-STD-867	Temper Etch Inspection
AMS-S-13165*	Shot Peening of Metal Parts*
MIL-STD-1501*	Chromium Plating, Low Embrittlement, Electrodeposition*
MIL-STD-868*	Nickel Plating, Low Embrittlement, Electrodeposition*
MIL-STD-869*	Flame Spraying*
MIL-STD-870	Cadmium Plating, Low Embrittlement, Electrodeposition
MIL-C-83488	Aluminum Plating, Ion Vapor Deposited
MIL-C-26074	Electroless Nickel Plating
MIL-A-8625	Anodic Coatings for Aluminum and Aluminum Alloys

* Overhaul processes applied to functional surfaces only.
All other overhaul processes applied to marking surfaces.

Test Matrix Discussion
The test matrix was selected to provide sufficient information to determine if marks applied with DPM processes on normal part marking surfaces survive normal aircraft landing gear part overhaul conditions for steel and aluminum parts. If the marks survive the selected test matrix of *Symbol*, *Data*, *DPM Processes*, *Materials*, *Surfaces*, *Topographies*, and *Overhaul Processes*, then the test matrix should be expanded. If the marks do not survive the selected test matrix, then the test program should be discontinued because there is no reason to believe that the marks on steel or aluminum would survive an overhaul environment. Note that if the marks do not survive the selected test matrix, there is no reason to believe that the marks would not survive an overhaul environment for other materials, such as titanium, which are subjected to different overhaul processes than steel and aluminum.

Symbol
The Data Matrix™ symbol was selected because it is the dominant machine readable mark for DPM. The Data Matrix™ symbol may contain several hundred characters in a relatively small space.

Data
The data content of 40 characters and 20 characters was selected because it provides sufficient information to track a part. In addition, the data content meets the primary objective of the test program to determine if the marks will survive an overhaul environment. For implementation, the data content would have to be determined by the Department of Defense or the USAF.

DPM Processes
The DPM processes were selected based on the NASA Technical Handbook 6003. Most of the selected processes were reported to provide safe marks for safety critical parts. All the selected processes were reported to provide lifetime traceability. Several processes were omitted from the test program because the processes were: under development, reported not to provide lifetime traceability, and/or offered no advantages over other processes that were already selected. Table 1 outlines the DPM processes that were selected and omitted.

Materials
The 4340 steel and the 7075-T73 aluminum were selected for material availability. Both materials are representative of landing gear materials and both materials duplicate the strength, hardness, and surface finish of landing gear materials.

The marks were applied to the base materials before any protective coatings were applied. Marks must be applied to the base materials if they are to survive an overhaul environment. Note that marks may be applied to the protective coatings without damaging the protective coating or the base material. These marks may survive an operational environment. However, these marks would not survive an overhaul environment unless they penetrate into the base material. If they penetrate into the base material, the functionality of the protective coating may be compromised near the mark.

The steel was marked before and after heat treatment to determine if the marks survive heat treatment. Applying the marks after heat treatment allows existing parts to be marked. Applying the mark before heat treatment is consistent with existing landing gear practices of applying the serial number before heat treatment. In addition, the marks may be more easily applied before heat treatment. If the marks degrade the material properties, the heat treatment process may mitigate any degrading effects.

Surfaces
The flat surface was selected for ease of manufacture, delivery, and processing of the coupons. Marks reportedly read well on flat surfaces. Marks also reportedly read well on curved surfaces provided that the marks occupy a maximum of one third of the diameter of the curve.

Topographies
The smooth surface with a surface roughness of 125RMS was selected because it is a typical surface roughness for landing gear parts. Marks reportedly read well for surface roughness ranges of 64RMS to 256RMS.

Overhaul Processes

The overhaul processes were selected because they are normal aircraft landing gear part overhaul processes that are applied to marking surfaces. Marks are applied to marking surfaces in contrast to functional surfaces which include stress critical surfaces, wear surfaces, sealing surfaces, etc. Both a marking surface and a functional surface may be structural. A marking surface is distinguished by a comparatively large and uniform area, while a stress critical area for a functional surface is distinguished by an abrupt geometry change such as a radius. The marking surface of a landing gear part typically has a corrosion protection system consisting of protective plating and painting, while the functional surface of a landing gear part typically has a high tolerance wear resistance surface consisting of the base material or hardened plating.

A mark must survive the overhaul processes for the marking surface. However, a mark may be protected during overhaul processes that affect the functional surfaces only. For example, a mark must survive all the chemical stripping environments because both the marking and functional surfaces are exposed to the environments and simple masking is not possible. Similarly, a mark must survive the abrasive blasting preparation for the protective plating processes for a marking surface. However, it is not necessary for a mark to survive the abrasive blasting processes for hardened plating or to have hardened plating applied directly over the mark. The hardened plating for functional surfaces include: chrome plate, nickel plate, flame spray coating, and HVOF coating.

The shot peening process is more difficult to categorize for marking and functional surfaces. Shot peening introduces a compressive residual stress in the surface and is used to improve the fatigue life of a part. It is a somewhat difficult process to control, and landing gear designers typically do not rely on it for fatigue improvements. However, it is commonly used for landing gear parts. It is applied to fatigue critical areas to increase the fatigue life, and it is applied as part of the surface preparation for hardened plating to recover the fatigue debit of the plating processes.

For the test program, shot peening was considered to be applied to a functional surface. A mark should not be located in a fatigue critical area or a plating area that requires shot peening. If a part mark were shot peened, it is questionable if there is an engineering benefit because the shot peen surface coverage for the mark impressions would be questionable. It is technically possible and relatively simple to mask a mark for shot peening, but masking does add an additional overhaul process control.

Table 1: DPM Process Selection

Included DPM Processes

Process	Safe for Part	Traceability	Comments
Dot Peen	Safe	Lifetime	
LaserShot™ Peen	Safe	Lifetime	
Micro-Mill	Safe	Lifetime	
Laser Bond	Safe	Lifetime	
Laser Etch	Unknown	Lifetime	• May degrade the material.
Gas Assisted Laser Etch (GALE)	Unknown	Lifetime	• May degrade the material.
Laser Engrave	Unknown	Lifetime	• May degrade the material.
Laser Induced Surface Improvement (LISI)	Unknown	Lifetime	• May degrade the material.
Vibropeen Steel Stamp	Safe	Lifetime	• Existing USAF processes. • Not machine readable marks. • Included for a comparison between existing USAF processes and other processes.

Omitted DPM Processes

Process	Safe for Part	Traceability	Comments
Abrasive Blast	Safe	Lifetime	• A difficult process to control. • No benefit over the other impression methods.
Build Up (Flame Spray, HVOF)	Safe	Not Lifetime	• Process under development. • Will not survive the overhaul environment. • May survive the operational environment.
Cast / Mold	Safe	Lifetime	• Process under development.
Electro-Chemical Etch	Safe	Lifetime	• No benefit over the impression methods. • May degrade the material.
Forge / Mold	Safe	Lifetime	• Process under development.
Ink / Paint	Safe	Not Lifetime	• May survive the operational environment if applied to a painted surface.
Laser Induced Vapor Deposition (LIVD)	Safe	Lifetime	• Used to apply marks to transparent materials.
Plate and Remove	Safe	Not Lifetime	• Will not survive the overhaul environment. • May survive the operational environment.
Thin Film Deposition	Safe	Not Lifetime	• A difficult process to apply marks to large parts. • Will not survive the overhaul environment. • May survive the operational environment.

TEST PROCEDURES

Coupon Testing

1. The test matrix was developed and the testing was conducted by the ALGLE Program. The test matrix was accomplished by processing and decoding marks on several coupons. Figure 1 contains a schematic image of a coupon. The coupon drawings are contained in Appendix A. The testing focused on normal part mark locations for landing gear parts and normal aircraft landing gear part overhaul conditions.

Coupon Manufacturing

1. The coupons were manufactured by NorthWest Machining and Manufacturing (NWMM).
2. The coupon manufacturing documentation is contained in Appendix B.

Coupon Marking

1. The coupons were marked by Robotic Vision Systems Incorporated (RVSI).
2. The coupon marking documentation is contained in Appendix C.

Coupon Overhaul Process Survivability Testing

1. The coupons were processed by the ALGLE Program and OO-ALC/MANP.
   - 1.1 The coupons were processed at the OO-ALC Landing Gear Overhaul Facility.
   - 1.2 The overhaul process documentation is contained in Appendix D.
   - 1.3 Images of the coupons after different processes are contained in Appendix E.
2. The decoding operations were performed by the ALGLE Program.
   - 2.1 The coupons were decoded at the OO-ALC Landing Gear Overhaul Facility in a laboratory environment.
   - 2.2 The decoding documentation is contained in Appendix F.
   - 2.3 Images of the marks after different processes are contained in Appendix G.

General Test Procedures

1. Two S1A coupons were processed as listed in Table 2.
   - 1.1 One coupon was processed with masking for damaging overhaul processes.
   - 1.2 One coupon was processed and then replaced with another coupon after damaging overhaul processes.
2. Two S1B coupons were processed as listed in Table 2.
   - 2.1 One coupon was processed with masking for damaging overhaul processes.
   - 2.2 One coupon was processed and then replaced with another coupon after damaging overhaul processes.
3. Two A1A coupons were processed as listed in Table 3.
   - 3.1 One coupon was processed with masking for damaging overhaul processes.
   - 3.2 One coupon was processed and then replaced with another coupon after damaging overhaul processes.
4. After each overhaul process, decoding operations were performed as listed in Table 4.

Figure 1: Coupon Schematic

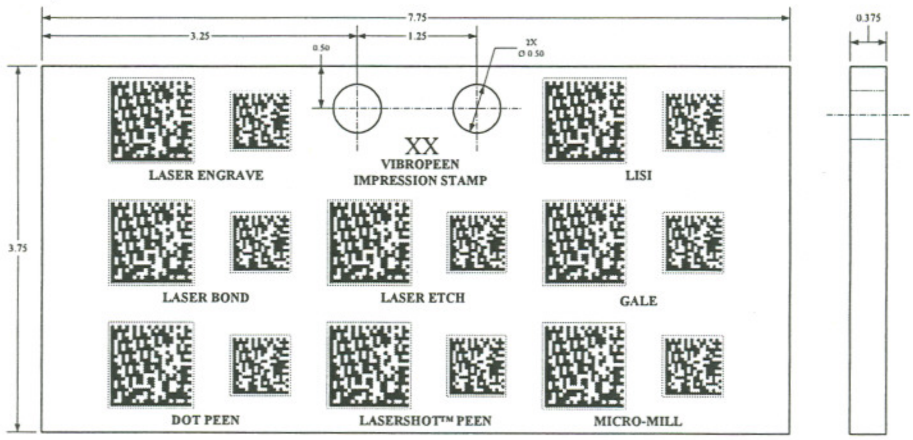


Table 2: Overhaul Processes for the Steel Coupons

1. Fluorescent Magnetic Particle Inspect per ASTM E1444.
   1.1 Use full wave direct current (FWDC), wet continuous method, fluorescent type with the following acceptance/rejection criteria: NO INDICATIONS ALLOWED. The inspector performing the inspection will be certified to a Level II with the inspection procedures developed by a Level III as specified in NAS-410.
2. Paint per MIL-STD-7179.
   2.1 One Coat Primer per MIL-P-85582 Type I, Class 2.
   2.2 Two Top Coats per MIL-C-85285, Type I.
3. Paint Strip per MIL-STD-871 (T.O. 4S-1-182).
4. Abrasive Blast per MIL-STD-1504, Abrasive Media (Plastic Media) per MIL-P-85891.
5. Abrasive Blast per MIL-STD-1504, Abrasive Media (Glass Media) per MIL-G-9954.
6. Temper Etch per MIL-STD-867.
7. Shot Peen per AMS-S-13165, Intensity 0.006A to 0.010A, Shot S-110.
   7.1 Mask Marks as Shown in Figure 2.
8. Shot Peen per AMS-S-13165, Intensity 0.006A to 0.010A, Shot S-110.
   8.1 One Coupon Only.
9. Chrome Plate per MIL-STD-1501, Type II, Class 2, Thickness 0.001INCH - 0.003 INCH.
   9.1 Mask Marks as Shown in Figure 2.
10. Chrome Plate Strip per MIL-STD-871.
11. Nickel Plate per MIL-STD-868, Type II, Thickness 0.001INCH - 0.003 INCH
    11.1 Mask Marks as Shown in Figure 2.
12. Nickel Plate Strip per MIL-STD-871.
13. Abrasive Blast per MIL-STD-1504, Abrasive Media (Garnet Media) per MIL-A-21380.
    13.1 One Coupon Only.
14. Cadmium Plate per MIL-STD-870, Type II, Class 1: (Thickness 0.001 INCH).
15. Cadmium Plate Strip per MIL-STD-871 (T.O. 4S-1-182, with Phosphoric Acid Dip).
16. IVD Aluminum Plate per MIL-DTL-83488, Type II, Class 1: (Thickness 0.001 INCH).
17. IVD Aluminum Plate Strip per MIL-STD-871.
18. Electroless Nickel Plate per MIL-C-26074, Class 1, Grade A: (Thickness 0.001 INCH).
19. Electroless Nickel Plate Strip per MIL-STD-871.
20. Abrasive Blast per MIL-STD-1504, Abrasive Media (Grit Media) per MIL-G-5634.
    20.1 Mask Marks as Shown in Figure 2.
21. Abrasive Blast per MIL-STD-1504, Abrasive Media (Grit Media) per MIL-G-5634.
    21.1 One Coupon Only.
22. Abrasive Blast per MIL-STD-1504, Abrasive Media (Aluminum Oxide Media) per MIL-S-17726.

Table 3: Overhaul Processes for the Aluminum Coupons

1. Fluorescent Penetrant Inspect per ASTM E1417.
   1.1 Use Type I, Level 3 or 4, Method B or C, with the following acceptance/rejection criteria: NO INDICATIONS ALLOWED. The inspector performing the inspection will be certified to Level II with the inspection procedures developed by a Level III as specified in NAS-410.
2. Paint per MIL-STD-7179.
   2.1 One Coat Primer per MIL-P-85582 Type I, Class 2.
   2.2 Two Top Coats per MIL-C-85285, Type I.
3. Paint Strip per MIL-STD-871 (T.O. 4W-1-61).
4. Abrasive Blast per MIL-STD-1504, Abrasive Media (Plastic Media) per MIL-P-85891.
5. Shot Peen per AMS-S-13165, Intensity 0.006A to 0.010A, Shot S-110.
   5.1 Mask Marks as Shown in Figure 2.
6. Shot Peen per AMS-S-13165, Intensity 0.006A to 0.010A, Shot S-110
   6.1 One Coupon Only.
7. Abrasive Blast per MIL-STD-1504, Abrasive Media (Grit Media) per MIL-G-5634.
   7.1 Mask Marks as Shown in Figure 2.
8. Abrasive Blast per MIL-STD-1504, Abrasive Media (Grit Media) per MIL-G-5634.
   8.1 One Coupon Only.
9. Flame Spray per MIL-STD-869, Type I, Thickness 0.025 INCH - 0.050 INCH.
   9.1 Mask Marks as shown in Figure 2.
10. Anodize per MIL-STD-8625, Type II, Class 1.
11. Anodize Strip per MIL-STD-871 (T.O. 4W-1-61).
12. Abrasive Blast per MIL-STD-1504, Abrasive Media (Glass Media) per MIL-G-9954.
    12.1 One Coupon Only.
13. Abrasive Blast per MIL-STD-1504, Abrasive Media (Plastic Media) per MIL-P-85891.

Figure 2: Mark Masking

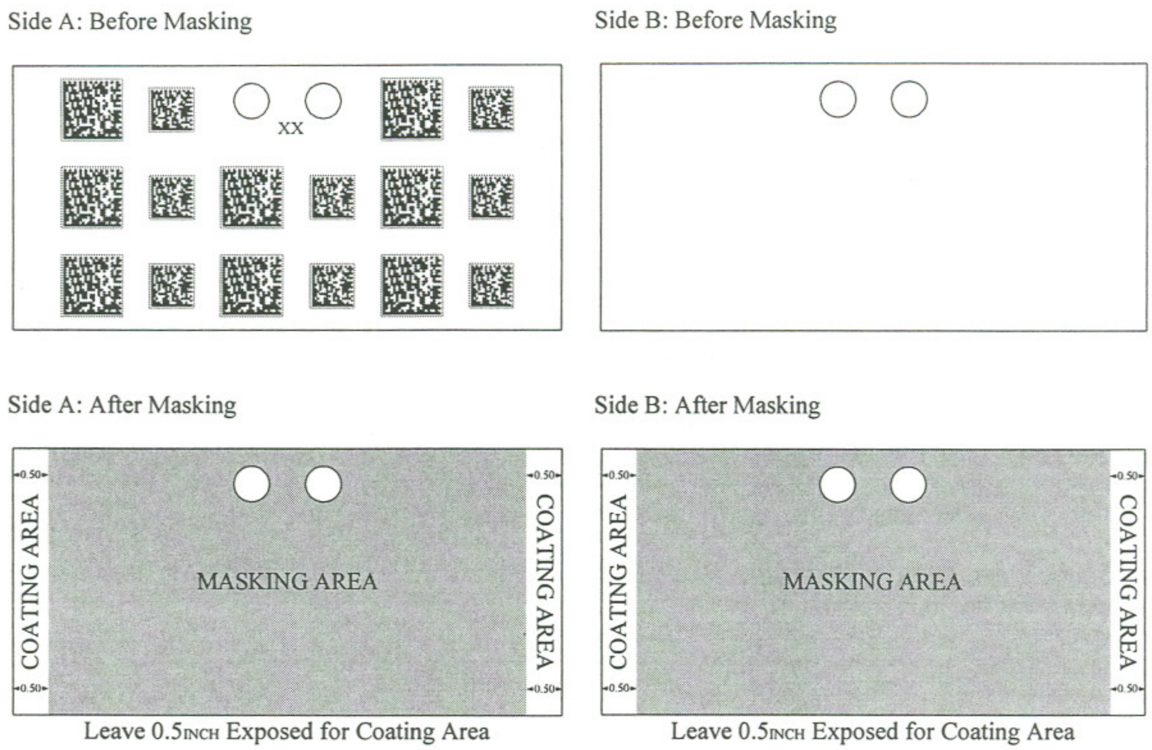


Table 4: Decoding Operations

1. Rank the mark damage based on visual appearance.
    1.1 Low Damage: Mark Easily Visible
    1.2 Medium Damage: Mark Visible / Observable and Significant Change in Contrast
    1.3 High Damage: Mark Not Easily Visible / Mark Not Visible
2. Perform the decoding operations with the MXi handheld reader.
    2.1 Successful Decode: Mark decodes: 1/1 attempts.
    2.2 Successful Decode: Mark decodes: 1/5 attempts.
    2.3 Unsuccessful Decode: Mark does not decode: 0/5 attempts.
    2.4 If debris is observed on the mark, clean the mark with a Scotch Pad and repeat the decoding operation.
3. Perform the decoding operations with the DMx fixed station reader.
    3.1 Only for coupons replaced after damaging overhaul processes.
    3.2 Successful Decode: Mark decodes: 10/10 attempts.
    3.3 Unsuccessful Decode: Mark does not decode: 0/10 attempts.

RESULTS AND DISCUSSION

Results

All the test results are presented in terms of the coupon part numbers S1A, S1B, and A1A which contain basic information about the material and when the material was marked. Coupon S1A was 4340 steel (S) that was marked after (A) heat treating to 260 ksi UTS. Coupon S1B was 4340 steel (S) that was marked before (B) heat treating to 260 ksi UTS. Coupon A1A was 7075-T73 aluminum (A) that was marked after (A) heat treating. Detailed test results are contained in Appendix E through Appendix G.

A summary of the test results is contained in Table 5 through Table 10. Table 5 contains mark survivability data for coupons S1A, S1B and A1A. The table provides data for the cumulative processing, and it provides data with painting and protective plating processes excluded. The table also provides the final decoding results for the cumulative processing. Marks with at least a 75% survivability were highlighted in green. A 75% survivability was considered sufficient to consider the marks for further development and testing. Note that all the decoding was conducted in a laboratory environment with ambient lighting by one well educated and well trained operator. Also note that the summary test results for the steel coupons only include test data for steel coupons that were cleaned with an abrasive scotch pad prior to decoding. Finally note that the summary test results are for the 40 character marks, since no significant differences between the 40 character and the 20 character marks were observed. Table 6 through Table 9 contain images of the marks before and after processing. Table 10 contains data for the depth of the mark cells as measured with a dial depth gage.

Definition of Mark Survivability

For the test program, three methods were used to assess mark survivability through the overhaul processes. A qualitative visual damage estimate was used as an overview. A quantitative survivability measurement was conducted with an MXi handheld reader after each overhaul process. After several processes, another quantitative survivability measurement was conducted with a DMx Auto ID+ fixed station reader. The visual damage estimate would be useful to asses basic mark damage or for an operator to locate a mark. The MXi handheld reader measurement would be useful for an operator to decode the mark in an overhaul environment. The DMx Auto ID+ fixed station reader measurement may be useful for an operator monitoring mark quality during the marking process or for a mishap investigator who must decode the mark. For daily use in a landing gear overhaul environment a fixed station reader would not be appropriate.

For the test program, the definition of mark survivability was the ability to successfully decode the mark with an MXi handheld reader. With this definition, the mark survivability could change with the operator, the environment, or with an improved handheld reader.

For the test program, the definition of lifetime traceability was the ability to successfully decode the mark with an MXi handheld reader after each overhaul process. With this definition, the lifetime traceability could change with the operator, the environment, or with an improved handheld reader.

Damaging Overhaul Processes

The testing identified abrasive blasting as the most damaging overhaul processes. The abrasive blasting processes remove an estimated 0.0001in. to 0.0005in. of base material. The chemical stripping processes were not identified as particularly damaging overhaul processes. The indication was that the chemical stripping processes are designed to remove painting and protective plating and do not actually remove the base material. For example, for the steel coupons, the most mark damage occurred during the abrasive blasting for the plating preparation. The actual plating process and the consequent chemical stripping processes did not appear to further damage the marks. The aluminum provided an exception with anodizing and anodize stripping where an estimated 0.001in. to 0.002in. of base material is removed. For the marks with depth, material removal within a mark cell is also expected, and so a net change in mark cell depth may be insignificant. For the marks with little or no depth, the marks are expected to be highly damaged.

Robust / Insensitive Marks

The results in Table 5 through Table 10 demonstrate that dot peen and micro-mill marks are the most robust machine readable marks for both steel and aluminum. Dot peen and micro-mill marks were observed to have fewer potential problems with protective platings, since the protective platings such as cadmium plating or anodizing uniformly covered the mark cells. The results also indicate that laser engrave marks perform reasonably well for both steel and aluminum. The depth measurements in Table 10 provide data that explains why the robust marks were able to survive the overhaul environment. Dot peen, micro-mill, and laser engrave were the only machine readable marks with consistently measurable depth.

The results for the steel that was marked after heat treatment are somewhat confounded since none of the marks performed reasonably well. The highest survivability was 50%. The results for the aluminum that was marked after heat treatment are also somewhat confounded since all of the marks performed reasonably well. The lowest survivability was 82%. However, the results for the steel that was marked before heat treatment discriminate dot peen and micro-mill marks as the most robust marks. Laser engrave marks also perform reasonably well.

The difference in survivability between the steel that was marked before and after heat treatment for the dot peen marks is attributed to the difference in the mark depths. The increase in survivability from 40% to 80% with all the processes included, and from 47% to 100% with the painting and protective plating processes excluded, is attributed to a difference in depth from 0.001in. to 0.003in. The difference in survivability between the steel that was marked before and after heat treatment for the micro-mill marks was attributed to a difference in the actual marking process. Different tooling and different cell spacing were used for the steel that was marked before and after heat treatment. It is not known why this occurred. The difference in survivability between the dot peen marks and the laser engrave marks is attributed to the difference in mark cell shape since both marks had similar depths. The test data indicates that the reader is able to detect a contrast change in the shadowing of the round mark cell shape of the dot peen mark better than for the square cell shape of the laser engrave mark.

The marks were masked for two damaging processes that are applied to functional surfaces: shot peening and grit blasting. The masking for shot peening was an additional overhaul process control. The masking for grit blasting was part of the standard overhaul process controls. The test data on the individual coupons indicates that without masking for shot peening, the robust marks on steel may survive, while all the marks on aluminum will be highly damaged by the S230 shot. The test data on the individual coupons indicates that without masking for grit blasting, all of the marks on steel and aluminum will be highly damaged by the 24 grit aluminum oxide. Note that grit blasting is an abrasive blasting process with 24 grit aluminum oxide, and it is a different type of abrasive blasting than plastic blasting, glass blasting, garnet blasting, or aluminum oxide blasting with 100 grit aluminum oxide. It is used to roughen a surface prior to applying a hardened plating.

The micro-mill marks had a unique clogging problem. The abrasive blasting media frequently lodged in the mark cells and clogged the mark cells. Additionally, if the marks were masked for shot peening or abrasive blasting, the mask material frequently lodged in the mark cells and clogged the mark cells. The clogging problem may be reduced by decreasing the depth of the micro-mill marks and by including tapered sides with corner radii.

The test data demonstrates that the robust dot peen and micro-mill marks with sufficient depth will survive the overhaul processes with additional process controls to mask the mark for shot peening and to clean the mark before decoding. The test data also demonstrates that none of the marks provide lifetime traceability by decoding after each process. For example, the dot peen mark that was marked on the steel coupon before heat treatment demonstrated 100% survivability when painting and protective plating were excluded. The mark did not demonstrate lifetime traceability with 80% survivability when painting and protective plating were included. The test data demonstrates the problem of achieving a reasonable mark depth on heat treated steel. The dot peen and the laser engrave marks did not conform to their depth requirement of 0.008in. to 0.016in. when marked after heat treatment. Marking heat treated steel is expected to continue to be problematic. The test data does demonstrate that marking before heat treatment is feasible and a reasonable depth can be achieved. However, the dot peen and the laser engrave marks still did not conform to their depth requirement of 0.008in. to 0.016in. when marked before heat treatment.

Non-Robust / Sensitive Marks

The results in Table 5 through Table 10 demonstrate that laser bond, lasershot peen, laser etch, GALE, and LISI were the non-robust machine readable marks for both steel and aluminum. Furthermore, the marks provided several potential issues with protective platings. It was questionable if the protective platings over the laser marks would be functional, and to qualify the laser marks, the integrity of the coatings would have to be tested. The depth measurements in Table 10 explain why the non-robust marks did not survive the overhaul environment. Laser bond, lasershot peen, laser etch, GALE, and LISI did not have a measurable depth based on a depth gage with an accuracy of ±0.0005in.

A critical point for consideration for the non-robust marks is that they were all highly damaged by garnet blasting. This is a typical paint stripping process as well as a typical plating preparation process for marking surfaces. If the marks do not survive these overhaul environments, then the intermediate labeling and paperwork documentation must be relied on for lifetime traceability. It is frequently suggested that a non-robust mark may be reapplied. However, it is questionable if reapplying a mark offers improvements over reapplying a label.

Cleaning and Backfilling

The steel coupons and marks were cleaned with an abrasive scotch pad after several overhaul processes. Overall, there was an average 18% improvement in survivability when the coupons were cleaned. When only the robust marks were considered, there was an average 46% increase in survivability. Cleaning improved the dot peen survivability by apparently leaving a clean surface and backfilling the cells with the cleaning debris. When the non-robust marks were considered, there was an average 3% increase in survivability. For several of the non-robust marks, cleaning damaged the marks. For example, for the laser bond mark, there was an average decrease of 8% in survivability after cleaning.

Attempts were made to backfill the dot peen and micro-mill marks to improve the survivability. A dry erase ink marker was used as the backfill material. The backfill efforts were not successful, since wiping the surface after the backfill to create a clean surface removed the backfill material from the mark. Backfilling the micro-mill marks was somewhat more successful. However, it was prohibitively time consuming. Additionally, backfill with the porous protective plating, such as cadmium plating, was not successful, since the plating absorbed the backfill material.

Human Readable Marks and Machine Readable Marks

The qualitative visual test data indicates that the current DPM processes for landing gear parts of vibropeening and impression stamping are robust. The test data indicates that human readable marks may outperform machine readable marks for lifetime traceability. An operator may be able to discern a mark through a discolored surface, plating, or painting better than a reader could. For processes where a machine readable mark does not decode efficiently the human readable mark could be used for lifetime traceability.

The vibropeening and impression stamping marks were damaged by the same processes that damaged the machine readable marks. Comparing the images from the abrasive blasting indicates that the robust dot peen and micro-mill marks may outperform the vibropeen mark. Furthermore, using a controlled machine marking process for the human readable mark would standardize characters which could increase traceability through improved character clarity.

For the steel coupons that were marked after heat treatment, it is noted that the vibropeening and impression stamping performed relatively well, since the marks sustained little damage from the overhaul processes, and they maintained their original appearance. However, it is noted that the initial ranking for the marks was medium damage, indicating that the marks were difficult to locate as marked. The initial ranking was essentially maintained throughout the test program.

Operator Training

Operator training to handle and use machine readable marks would be required for implementation. This would likely include training to recognize and protect a mark during processing, and training to decode a mark. The training to recognize and protect a mark would likely include training for: disassembly and nick and burr operators to recognize a mark and not remove a mark with grinding wheels; masking a mark for shot peening; and masking a mark for grit blasting. Training to decode a mark may consist of locating the mark, cleaning the mark area, and gaining familiarity with the reader. One of the primary guidelines for the testing was the mark(s) and reader(s) must function as an automatic identification and tracking technology to assist an operator in collecting data directly from landing gear parts in an overhaul environment. Operator training should be consistent with the guideline.

Overhaul Process Controls or Increased Mark Depth

The testing demonstrates that marks survive with masking for shot peening and grit blasting which are applied to functional surfaces. Masking for shot peening would be performed prior to shot peening and would be an additional overhaul process control. Masking for grit blasting would be performed as part of the standard plating preparation. An option to employing masking for shot peening as an additional overhaul process control would be to pursue a deeper mark that would not require masking. For steel, the test data indicates that a significantly deeper mark may not be required, since the dot peen marks (0.003in) and the micro-mill marks (0.026in) on the steel that was marked before heat treatment survived the shot peening. However, for aluminum the test data indicates that a significantly deeper mark would be required, since the dot peen marks (0.003in) and the micro-mill marks (0.026in) on the aluminum that was marked after heat treatment did not survive and were highly damaged by the shot peening. Pursuing larger and deeper marks would limit the practicality of the mark by limiting the amount of parts that could be marked and would also reduce the mark benefits of mark size and high data density.

Zero Contrast Readers

Several zero contrast readers or read through protective coating readers were reviewed as part of the research and development effort. There are several promising technologies that are under development. Only a thermal imaging reader and an ultrasound imaging reader were reviewed. Both readers were able to image several of the marks through one coat of primer and two coats of paint. The images were not as clear as the optical images and more refinement of the imagers and readers would be required. The images are in Appendix G. The zero contrast technologies are under development and continue to improve, but the optical imaging remains the most advanced and best performing technology for most applications and environments.

The test data indicates that a non-contact method of detecting depth change would be the best zero contrast technology. It may reduce cleaning before decoding and it may image depth changes through protective coatings.

Table 5: Mark Survivability Results for Coupons S1A, S1B, and A1A
S1A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment
S1B: 4340 Steel (260 ksi UTS) Marked Before Heat Treatment
A1A: 7075-T73 Aluminum Marked After Heat Treatment

	Mark Survivability: All Processes Included*		Mark Survivability: Painting and Protective Plating Processes Excluded*		Final Decoding Results*	
Coupon S1A	**20 Processes Total**		**15 Processes Total**		**After 20 Processes**	
DPM Process	**Visual Estimate**	**MXi Handheld Reader**	**Visual Estimate**	**MXi Handheld Reader**	**MXi Handheld Reader**	**DMx Auto ID+ Fixed Reader**
1 - Dot Peen	80%	40%	100%	47%	No	No
2 - LaserShot™ Peen	30%	10%	40%	13%	No	No
3 - Micro-Mill	100%	45%	100%	47%	No	Yes
4 - Laser Bond	30%	30%	40%	40%	No	No
5 - Laser Etch	80%	50%	100%	67%	No	No
6 - GALE	30%	25%	40%	33%	No	No
7 - Laser Engrave	80%	50%	100%	67%	No	No
8 - LISI	30%	30%	40%	40%	No	No
9 - Vibropeen	80%		100%			
10 - Impression Stamp	80%		100%			

Coupon S1B	**20 Processes Total**		**15 Processes Total**		**After 20 Processes**	
DPM Process	**Visual Estimate**	**MXi Handheld Reader**	**Visual Estimate**	**MXi Handheld Reader**	**MXi Handheld Reader**	**DMx Auto ID+ Fixed Reader**
1 - Dot Peen	90%	80%	100%	100%	Yes	Yes
2 - LaserShot™ Peen	30%	30%	40%	40%	No	No
3 - Micro-Mill	100%	75%	100%	93%	Yes	Yes
4 - Laser Bond	30%	25%	40%	33%	No	No
5 - Laser Etch	60%	40%	80%	53%	No	No
6 - GALE	30%	20%	40%	27%	No	No
7 - Laser Engrave	80%	55%	87%	73%	No	No
8 - LISI	30%	25%	40%	33%	No	No
9 - Vibropeen	100%		100%			
10 - Impression Stamp	100%		100%			

Coupon A1A	**11 Processes Total**		**8 Processes Total**		**After 11 Processes**	
DPM Process	**Visual Estimate**	**MXi Handheld Reader**	**Visual Estimate**	**MXi Handheld Reader**	**MXi Handheld Reader**	**DMx Auto ID+ Fixed Reader**
1 - Dot Peen	82%	82%	100%	100%	Yes	Yes
2 - LaserShot™ Peen	82%	82%	100%	100%	Yes	Yes
3 - Micro-Mill	100%	82%	100%	100%	Yes	Yes
4 - Laser Bond	55%	82%	75%	100%	Yes	Yes
5 - Laser Etch	82%	82%	100%	100%	Yes	Yes
6 - GALE	82%	82%	100%	100%	Yes	Yes
7 - Laser Engrave	82%	82%	100%	100%	Yes	Yes
8 - LISI	82%	82%	100%	100%	Yes	Yes
9 - Vibropeen	82%		100%			
10 - Impression Stamp	100%		100%			

Decoding Legend		Decoding Legend		Decoding Legend	
Visual Estimate	**MXi Handheld Reader**	**Visual Estimate**	**MXi Handheld Reader**	**MXi Handheld Reader**	**DMx Auto ID+ Fixed Reader**
Above 75%	Above 75%	Above 75%	Above 75%	1 / 1 or 1 / 5	10 / 10
Below 75%	Below 75%	Below 75%	Below 75%	0 / 5	0 / 10

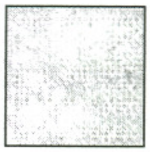
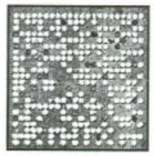
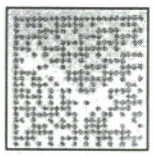
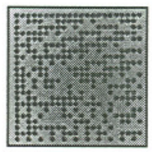
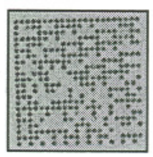
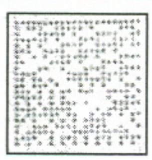
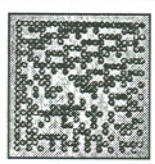
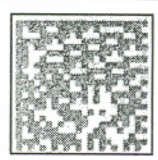
* Marks masked for shot peening with S230 shot and grit blasting with 24 grit aluminum oxide.

Table 6: Images of Initial Mark and Final Mark After Processes for Coupons S1A, S1B, and A1A *
S1A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment
S1B: 4340 Steel (260 ksi UTS) Marked Before Heat Treatment
A1A: 7075-T73 Aluminum Marked After Heat Treatment

DPM Process	S1A Initial Mark	S1A After Processes	S1B Initial Mark	S1B After Processes	A1A Initial Mark	A1A After Processes
1 - Dot Peen						
2 - LaserShot Peen						
3 - Micro-Mill						
4 - Laser Bond						
5 - Laser Etch						
6 - GALE						
7 - Laser Engrave						
8 - LISI						
9-Vibropeen 10-Impression Stamp						

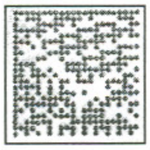
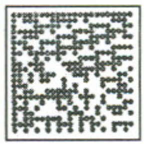
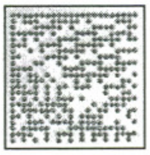
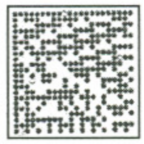
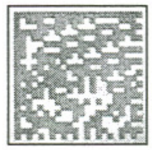
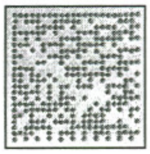
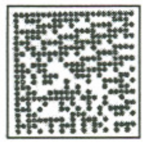
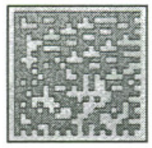
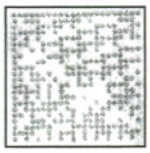
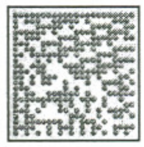
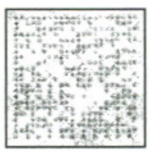
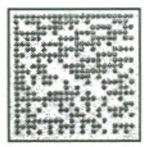
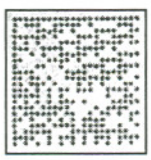
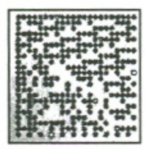
* Marks masked for shot peening with S230 shot and grit blasting with 24 grit aluminum oxide..

Table 7: Images of Marks After Abrasive Blasting Processes for Coupon S1A
S1A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment

	1 - Dot Peen	3 - Micro-Mill	7 - Laser Engrave	9-Vibropeen 10-Impression Stamp
Initial Mark				
Plastic Media				
Glass Media				
Garnet Media				
Aluminum Oxide Media (100 Grit Al_2O_3)				
Grit Media * (24 Grit Al_2O_3)				
Shot Peen Media **				

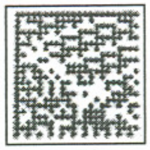
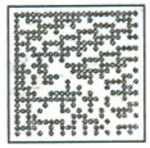
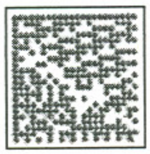
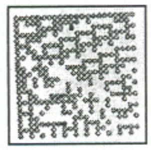
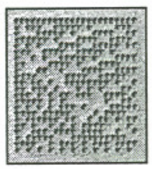
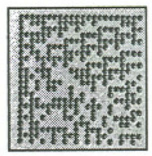
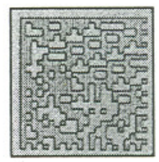
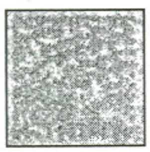
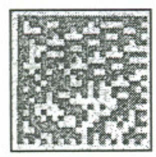
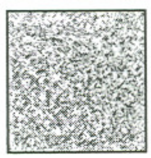
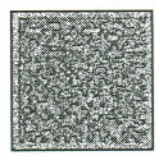
* For hardened plating preparation for a functional surface.
** For fatigue life improvement for a functional surface.

Table 8: Images of Marks After Abrasive Blasting Processes for Coupon S1B
S1B: 4340 Steel (260 ksi UTS) Marked Before Heat Treatment

DPM Process	1 - Dot Peen	3 - Micro-Mill	7 - Laser Engrave	9-Vibropeen 10-Impression Stamp
Initial Mark				
Plastic Media				
Glass Media				
Garnet Media				
Aluminum Oxide Media (100 Grit Al_2O_3)				
Grit Media * (24 Grit Al_2O_3)				
Shot Peen Media **				

* For hardened plating preparation for a functional surface.
** For fatigue life improvement for a functional surface.

Table 9: Images of Marks After Abrasive Blasting Processes for Coupon A1A
A1A: 7075-T73 Aluminum Marked After Heat Treatment

DPM Process	1 - Dot Peen	3 - Micro-Mill	7 - Laser Engrave	9-Vibropeen 10-Impression Stamp
Initial Mark				
Plastic Media				
Glass Media				
Grit Media * (24 Grit Al_2O_3)				
Shot Peen Media **				

* For hardened plating preparation for a functional surface.
** For fatigue life improvement for a functional surface.

Table 10: Mark Cell Depth
Average Depth in Inches Based on 3 Dial Gage Measurements *

DPM Process	Coupon S1A	Coupon S1B	Coupon A1A
1 - Dot Peen	0.001	0.003	0.005
2 - LaserShot Peen	0.000	0.000	0.000
3 - Micro-Mill	0.027	0.026	0.028
4 - Laser Bond	0.000	0.000	0.000
5 - Laser Etch	0.000	0.000	0.001
6 - GALE	0.000	0.000	0.000
7 - Laser Engrave	0.001	0.002	0.006
8 - LISI	0.000	0.000	0.000
9 - Vibropeen	0.001	0.005	0.003
10 - Impression Stamp	0.001	0.010	0.013

*A depth of 0.000in. indicates that no depth measurement could be taken.

CONCLUSIONS

The test program was conducted to evaluate the survivability of machine readable marks applied with direct part marking processes for normal aircraft landing gear part overhaul conditions. Specifically, the test program was to determine if the machine readable marks provide lifetime traceability for landing gear parts by surviving normal aircraft landing gear part overhaul conditions.

The test data demonstrates that the marks and readers do not provide a system for complete lifetime traceability. However, no automatic identification and tracking technology is known to provide the level of lifetime traceability that is being considered.

The test data demonstrates that the robust dot peen and micro-mill marks will survive the overhaul processes with additional process controls to mask the mark for shot peening and to clean before decoding. Laser engrave marks also perform reasonably well. The test data demonstrates that the non-robust laser bond, lasershot peen, laser etch, GALE, and LISI marks will not survive the overhaul processes. For all the marks, the survivability was strongly correlated to the mark depth. The test data also indicates that survivability depended on the reader ability to detect a contrast change between the mark surface and the mark cells.

The test data demonstrates that the robust marks may provide improved overhaul to overhaul traceability, and improved traceability in an overhaul environment. The improved traceability could be used to better track the number of overhauls for a part or to audit part traceability at critical points within an overhaul environment. The improved traceability could assist with better part data for mishap investigations.

The test data identified abrasive blasting as the most damaging overhaul processes. The chemical stripping processes were not identified as particularly damaging overhaul processes. The test data identified that the marks should be masked for two damaging processes that are applied to functional surfaces: shot peening and grit blasting. Masking for shot peening is an additional overhaul process control. Masking for grit blasting is part of the standard overhaul process controls.

The test data demonstrates the problem of achieving a reasonable mark depth on heat treated steel. The test data demonstrates that marking before heat treatment is feasible and a reasonable depth may be achieved. Marking heat treated steel is expected to continue to be problematic and is the primary problem for marking fielded landing gear parts. Marking heat treated steel may also benefit the landing gear manufacturer. While it is technically feasible to mark a part before heat treatment, it may be preferred to place the final mark on a part after heat treatment.

Finally, a note on the survivability of machine readable marks is provided. The dot peen mark that was marked on steel before heat treatment survived the overhaul processes with a 100% survivability when painting and protective plating were excluded. While this demonstrated the potential problem of painting and protective plating, it also demonstrated the robustness of the marks. The cumulative processing for the mark included at least five abrasive blasting processes with garnet media, cadmium plating, IVD aluminum plating, and electroless nickel plating. The mark was subjected to the chemical stripping environments for cadmium plating, IVD aluminum plating, electroless nickel plating, chrome plating, and nickel plating. The mark contained 40 characters of information in less than a 0.5in. by 0.5in. square area and decoded in less than 1 second without error. As a comparison, an equivalent human readable mark with 40 characters of information would be expected to occupy a 0.2in. by 4.0in. rectangular area and decode in approximately 45 seconds with additional decoding time required to check the error. There is not another existing automatic identification and tracking technology that could compete with the machine readable direct part mark under the same conditions in the overhaul environment. The research and development of marks and readers is continuing, and improvements in marking and reading may be expected.

RECOMMENDATIONS

Based on the test data, it is not recommended to implement a tracking system with the current machine readable direct part marks and readers. There is an indication of survivability and increased traceability over existing marks, but the decoding results for steel that is marked after heat treatment are not high enough to warrant implementation. It is still recommended to pursue a serial number tracking system with machine readable labels. It is also recommended to further evaluate the indications of increased traceability over existing direct part marks. It is recommended to pursue the development of the machine readable marks and readers. It is recommended to conduct a return on investment analysis to assist in determining how resources should be allocated between developing a serial number tracking system with labels or direct part marks.

Based on the test data, the guideline for a mark to survive an overhaul environment with no process controls is inherently conflicting with the current landing gear guideline for a mark depth of 0.004in. to 0.008in. For aluminum, the test data indicates that a significantly deeper mark would be required, since the dot peen marks (0.003in) and the micro-mill marks (0.026in) on the aluminum that was marked after heat treatment did not survive and were highly damaged by the shot peening. Pursuing larger and deeper marks would limit the practicality of the mark by limiting the amount of parts that could be marked and would also reduce the mark benefits of high data density. Pursuing a deeper mark for fielded parts may also impact safety. Further testing could be conducted to determine the minimum mark depth required to survive all overhaul processes without masking. This testing would be expected to confirm the expected problems. It is recommended to adapt an overhaul process control of masking marks for shot peening.

Based on the test data, it is recommended to pursue dot peen, micro-mill, and laser engrave marks for further development and testing. The focus of the development and testing would be to mark heat treated steel. It would also be to improve the marks: by achieving a sufficient depth of 0.004in. to 0.008in for survivability; and by including tapered sides and corner radii to reduce damage and clogging. The test data indicates that a round cell design would survive the overhaul process reasonably well, and a proposed cell design for dot peen, micro-mill, and laser engrave marks is provided in Figure 3. The test data indicates that the mark shape is critical for survivability and that there may be large differences in survivability due to small mark changes and enhancements. In fact, the actual details of the mark symbology could be critical for survivability. Developing an optimum mark is expected to require a significant development effort. Additional development work on a laser engrave mark would be to evaluate the removal of the suspected heat affected zone with an abrasive blasting process and to examine the issues of a non-uniform protective plating over the mark.

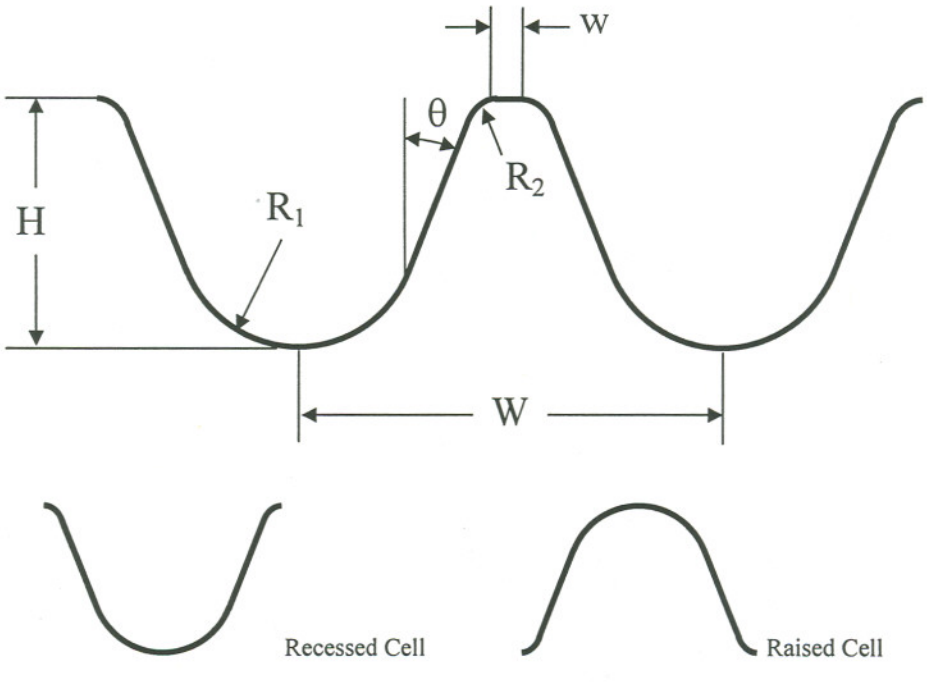
Further development and testing for marks could include emerging DPM processes. A review of the emerging DPM processes indicates that forged marks should be evaluated because the majority of landing gear parts are forged. A review of the cast, flame spray and HVOF marks indicates that they may not be suitable for landing gear parts. Landing gear parts are not cast. Flame spray and HVOF marks are expected to sustain damage during abrasive blasting or to be removed during HVOF stripping. All of the marks are expected to be large marks and have potential problems with mark size and high data density. Finally, a concern for a forged mark is that it must be applied early on in the manufacturing process. It may provide a questionable benefit over a dot peen or a laser engrave mark applied at the same early stage in the manufacturing process.

Based on the test data, it is recommended to pursue development and testing for human readable marks. The test data indicates that using a controlled machine marking process for the human readable mark would standardize characters which could increase traceability through improved character clarity. The test data also indicates that human readable marks may outperform machine readable marks for lifetime traceability. Human readable marks could be used as a backup to the more automatic machine readable marks. Based on the test data, it is recommended to pursue development and testing to quantify the differences between human readable marks and machine readable marks. Human readable marks could be used to better evaluate mark survivability by determining if either the human readable mark or the machine readable mark survives an overhaul environment. If the human readable mark outperforms the machine readable mark, it would indicate that reader imaging and decoding algorithms should be improved or that zero contrast readers should be developed. Part of the development and testing for human readable marks and machine readable marks should also be to include the effects of different operators.

Based on the test data, it is recommended to pursue the development and testing of readers. It is also recommended to pursue simple and effective methods for mark enhancement such as backfilling. It is also recommended to investigate zero contrast readers or read through protective coating readers. For all the reader technologies, it is recommended to pursue performance requirements that encourage reader competition. At the start of the test program, several bar code readers were evaluated, and the MXi handheld reader was selected because it was the only reader that could consistently decode the majority of the marks. Since the end of the test program, several reader companies have developed readers that may be well suited for decoding the marks. Reader competition is important since it may enable the Department of Defense or the USAF to require machine readable direct part marking and avoid a situation where a single company dominates tracking and logistics functions. Future reader development and testing should focus on a handheld reader that is suitable for an overhaul environment.

If further development and testing are pursued, it is recommended to conduct the testing on coupons before including additional complexities. The coupon testing should be the most economical method of identifying and solving problems. For further coupon testing, it is recommended to sequence processing to include abrasive blasting, protective plating, painting, and then chemical stripping.

Figure 3: Proposed Cell Design for Future Test Programs



- Proposed Cell Design Applicable to Recessed Cells and Raised Cells
- H (0.004 IN to 0.008 IN): Deep Enough to Survive Processes with Reasonable Masking
- W, w: Sufficient Cell Spacing to Reduce Cell Damage
- θ: Draft Angle to Reduce Cell Damage, Cell Clogging, and Cell Stress Concentration (Kt)
- R_1, R_2: Radii to Reduce Cell Damage, Cell Clogging, and Cell Stress Concentration (Kt)
- R_1, R_2: Radii Cells / Other Cell Shapes Will Be Rounded from Blasting Processes
- Consider Parabolic Cell Design or Hyperbolic Cell Design for Optimum Reflectivity

APPENDIX A
COUPON DRAWINGS