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MARCH 2004

TEST REPORT – DIRECT PART MARK TEST PROGRAM
IMPROVED DIRECT PART MARK MICROSCOPY TEST PROGRAM

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 IMPROVED DIRECT PART MARK MICROSCOPY TEST PROGRAM

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AGING LANDING GEAR LIFE EXTENSION PROGRAM

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INTRODUCTION

Under the Aging Landing Gear Life Extension (ALGLE) Program, a microscopy test program was conducted for geometry characterization and microstructure characterization of machine readable marks that are applied with the deep laser engrave direct part marking (DPM) process. 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 deep laser engrave marks have problematic geometry features or problematic microstructure features that would degrade the material properties of a part, and to determine if it is technically possible to remove the shallow heat affected zone from deep laser engrave marks with an abrasive blasting process. For the test program, the marks were considered controlled flaws, and a focus of the test program was to distinguish problematic features beyond the inherent controlled flaw size of the mark cell dimensions.

The test program was a research and development effort that addressed several recommendations from a previous test program. The final report for the previous test program was entitled *Direct Part Mark Microscopy Test Program GA-C24578*, and herein it is referred to as the previous test program. The previous test program identified: no problematic geometry features and no problematic microstructure features with dot peen marks; problematic geometry features with micro mill marks due to insufficient cell spacing and very sharp corner radii, but no problematic microstructure features with micro mill marks; no problematic geometry features with laser engrave marks, but problematic microstructure features with laser engrave marks applied after heat treatment due to a shallow heat affected zone approximately 0.001in. thick.

The test program focused on deep laser engrave marks because they provide a robust mark cell shape with a reasonable depth between 0.003in. to 0.009in. Compared to dot peening or micro milling, deep laser engraving may provide an optimum DPM process based on manufacturing considerations, and eliminate problems of marking heat treated steel, marking curved surfaces, and fixturing. The test program focused on representative landing gear materials that were high strength steel and high strength aluminum. To determine the severity of any problematic features or to determine the severity of the inherent controlled flaw size for steel and aluminum, additional mark and material characterization such as fatigue testing or stress corrosion cracking testing could be conducted.

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.

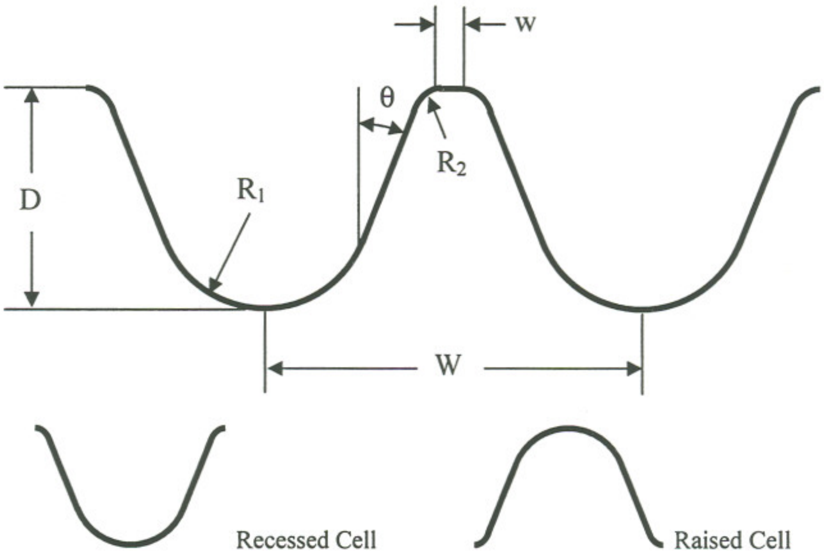
OBJECTIVES

The objectives were: to perform a geometry characterization and a microstructure characterization of marks applied with the deep laser engrave direct part marking (DPM) process; to determine if the marks have problematic geometry features or problematic microstructure features that would degrade the material properties of a part; and to distinguish problematic features beyond the inherent controlled flaw size of the mark cell dimensions.

The objective was to determine if it is technically possible to remove the shallow heat affected zone from deep laser engrave marks with abrasive blasting processes.

The objective was to develop robust deep laser engrave marks with the mark cell shape, mark cell depth, and consequent characteristics shown in Figure 1.

Figure 1: Proposed Robust Mark Cell Shape



- Proposed Cell Design Applicable to Recessed Cells and Raised Cells
- D (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)

TEST MATRIX AND DISCUSSION

Test Matrix

Symbol

Machine Readable Mark: Data Matrix™ (18 x 18)

Data

10 Random Numeric Characters

DPM Processes

Deep Laser Engrave: 0.008in. Deep

Materials

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

Surfaces

Marking Surface
Flat Surface
Smooth Surface, 125RMS

Abrasive Blasting Processes

Garnet Blasting for Steel (MIL-STD-1504 - Abrasive Blasting with Garnet Media)
10X or 1000% Surface Coverage
Glass Blasting for Steel and Aluminum (MIL-STD-1504 - Abrasive Blasting with Glass Media)
10X or 1000% Surface Coverage

Test Matrix Discussion

The test matrix was selected to address several recommendations from the previous test program. The test matrix was selected to provide sufficient information to perform geometry characterization and microstructure characterization of marks applied with the deep laser engrave DPM process. If marks were found to have no problematic features for the selected test matrix of *Symbol*, *Data*, *DPM Processes*, *Materials*, *Surfaces*, and *Abrasive Blasting Processes*, then the test matrix should be expanded. If marks were found to have problematic features, then methods to eliminate the problematic features should be investigated. Also, mark and material characterization such as fatigue testing or stress corrosion cracking testing should be conducted to determine the severity of any problematic features or to determine the severity of the inherent controlled flaw size for 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 10 characters was selected because it provides sufficient information to track a part. In addition, the data content meets the objectives of the test program. For implementation, the data content would have to be determined by the Department of Defense or the USAF.

DPM Processes

The deep laser engrave DPM process was selected because the marks provide a robust mark cell shape with a reasonable depth between 0.003in. to 0.009in. Compared to dot peening or micro milling, deep laser engraving may provide an optimum DPM process based on manufacturing considerations by eliminating problems of marking heat treated steel, marking curved surfaces, and fixturing.

Marks that were 0.008in. deep were selected because they are at the upper end of the depth range and would provide an estimate for the largest controlled flaw size. Additionally, if the abrasive blasting processes remove the shallow heat affected zone from marks that are 0.008in. deep, then testing marks with less depth would not be required.

The marks were applied to the base materials to survive an overhaul environment and to eliminate compromising protective coatings.

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 steel and aluminum were marked after heat treatment. Applying the marks after heat treatment allows existing parts to be marked.

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. 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.

Abrasive Blasting Processes

The abrasive blasting processes were selected because they are normal aircraft landing gear part overhaul processes. The abrasive blasting processes are applied to the marking surfaces of landing gear parts and are frequently used to remove shallow heat affected zones from landing gear parts. Garnet blasting was not applied to the marks on aluminum because garnet blasting is not used on aluminum landing gear parts. A 10X or 1000% abrasive blasting surface coverage was selected to determine if it is technically possible to remove the shallow heat affected zone from the marks.

TEST PROCEDURES

Coupon Testing

1. The test matrix was developed and the testing was conducted by the ALGLE Program. The test matrix was accomplished with several coupons. The coupon drawings are contained in Appendix A.

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 marking documentation is contained in Appendix C.

Coupon Processing

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.

Coupon Microscopy

1. The microscopy evaluation was conducted by the ALGLE Program.
   1.1 Microscope images of the mark surfaces and of the cross sections are contained in Appendix E.
   1.2 Microhardness data for the marks is contained in Appendix F.
   1.3 SEM EDX composition data for the marks is contained in Appendix G.

General Test Procedures

1. The microscopy evaluation was performed for coupons S2A and A2A.
   1.1 Geometry characterization was performed for all the marks.
   1.2 Microstructure characterization was performed for all the marks.

Geometry Characterization

1. The marks were examined with an optical microscope at 1X to 100X magnification.
2. The marks were examined with an SEM at 30X to 1000X magnification.
3. Surface SEM images of the mark cells were taken at 30X, 150X, and 1000X magnification.
4. Surface SEM images of the mark cells were taken at 30X magnification on a 45° tilt.
5. The depth of the mark cells was measured with a dial depth gage. Average values are provided.
6. The depth of the mark cells was measured with SEM software. Average values are provided.

Microstructure Characterization

1. The coupons were sectioned and polished to expose a mark cross section that contained a minimum of 5 cells.
2. Microhardness measurements were taken of the exposed cross section away from the marks.
   2.1 ASTM E 384 was used as a guide.
   2.2 For coupon S2A, a diamond pyramid hardness indenter was used with a 200g load and a 30 second dwell time.
   2.3 For coupon A2A, a diamond pyramid hardness indenter was used with a 50g load and a 30 second dwell time, and a 100g load and a 30 second dwell time.
   2.4 At least three mircohardness measurements were taken of the base material well away from the cell surface.
   2.5 At least three microhardness measurements were taken at depths less than 0.005inch from the cell surface.
3. Etching the exposed cross section near the marks was performed.
   3.1 ASTM E 407 was used as a guide.
   3.2 For coupon S2A, a 2% nital etchant (2%$HN0_3$ + 98% Ethanol (CH_3CH_2OH)) was used.
   3.3 For coupon A2A, a Flick etchant (9%HF + 13%HCl + 78%H_20) was used.
   3.4 Optical microscope images were taken of the etched cross section near the mark cells.

RESULTS AND DISCUSSION

Results
All the test results are presented in terms of the coupon part numbers S2A and A2A which contain basic information about the material and when the material was marked. Coupon S2A was 4340 steel (S) that was marked after (A) heat treating to 260 ksi UTS. Coupon A2A 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 1 through Table 4, and in Figure 2 and Figure 3. Table 1 contains data for the depth of the mark cells as measured with a dial depth gage and quantitative SEM software. Table 2 contains summary test results for the microhardness data. Figure 2 and Figure 3 contain summary plots of the microhardness data. Table 3 and Table 4 contain summary images of the marks. There are SEM images of the marks and optical images of the etched mark cell cross sections.

Geometry Characterization
The marks were examined with an optical microscope and a scanning electron microscope to provide a basic geometry characterization for the marks. The marks were examined at 1X to 1000X magnification. Representative images of the marks are contained in Appendix E. The SEM surface images show the mark cells and the adjacent base material. The marks had droplet features that were consistent with melting and resolidification as a laser traversed the surface. The marks also had raised rims that were consistent with debris ejection from the marks. There was an obvious difference between the marks and the coupon surface. The marks after glass blasting and garnet blasting had rough, blocky features that were consistent with a blasted surface. The raised rims were also removed by the glass blasting or the garnet blasting. There was no obvious difference between the marks and the coupon surface after glass blasting or garnet blasting. The SEM images indicate that the glass blasting or garnet blasting removed the shallow heat affected zone. The SEM cross section images and the optical cross section images demonstrate the robust mark cell shape with corner radii, tapered sides, and spacing. The images of the marks after glass blasting or garnet blasting demonstrate that abrasive blasting will round the mark corners: for the steel, the mark rims exhibited simple rounding; and for the aluminum, the mark rims exhibited significant rounding and material flow. The glass blasting on aluminum created a small lap near the mark rim. Compared to the depth of the mark, the lap would not be considered a significant flaw. Based on the geometry characterization, apart from the inherent controlled flaw of the mark, no other obvious material degradation was found. No evidence of micro cracking in the base material was found for any of the marks.

An energy dispersive x-ray (EDX) composition analysis was performed in conjunction with the SEM geometry characterization to examine the surface contamination of the different marks. The EDX composition data is contained in Appendix G. The EDX analysis of the mark shows the constituents of the steel and aluminum alloys. The marks after glass blasting had spectrum peaks for silicon which is consistent with glass contamination. The marks after garnet blasting had spectrum peaks for magnesium, aluminum, and silicon which are consistent with garnet contamination. Overall, embedded particles were detected but no other contaminants of significance were detected on the marks after blasting.

Table 1 summarizes the mark depths. The test data demonstrates that the mark depths did not change significantly after blasting. The changes in depth are less than 0.001in. It is not known how much of the mark, the surface, or both are removed due to blasting. For the marks on steel there is an indication that the marks were slightly deeper after blasting, which indicates that more of the mark was removed. For the marks on aluminum there is an indication that the marks are deeper before blasting which indicates that more of the surface was removed. Additionally, for marks on the aluminum, some marks had a raised center portion making them slightly less deep at the center than off the center. There was a very good correlation between the dial depth gage measurement and the SEM measurement. This indicates that the dial depth gage could be used as a simple method of measuring cell depth for mark quality verification and control.

Microstructure Characterization

Microhardness

The test data in Figure 2, Figure 3, and Table 2 demonstrates that there was minor softening for the deep laser engrave marks on steel, and no minor softening or minor hardening for the deep laser engrave marks on aluminum.

The test data demonstrates an obvious trend of minor softening for the marks on steel. The test data demonstrates no obvious trend of minor softening or hardening for the marks on steel after either glass blasting or garnet blasting. The test data indicates that the blasting processes may be removing the shallow heat affected zone from the surface and/or compressing the surface. For the marks, the minor softening extended approximately 0.004in. into the base material, and an equivalent controlled flaw size could be considered the mark cell dimensions plus approximately 0.004in. For the marks after glass blasting or garnet blasting, no minor softening or hardening was present, and an equivalent controlled flaw size could be considered the mark cell dimensions. Further material characterization testing, such as fatigue testing or stress corrosion cracking testing, would be required to distinguish any other material degradation effects.

The test data demonstrates no obvious trend for minor softening or minor hardening for the marks on aluminum. The test data demonstrates no obvious trend for minor softening or minor hardening for the marks on aluminum after glass blasting. The microhardness data had considerable variability less than 0.002in. from the cell surface. This was attributed to an edge effect of the free cell surface. The considerable variability was present with both a 100g load and a 50g load. The considerable variability in the microhardness data was less that 0.002in. from the cell surface for all the marks on aluminum, and an equivalent controlled flaw size could be considered the mark cell dimensions plus 0.002in. Further material characterization testing, such as fatigue testing or stress corrosion cracking testing, would be required to distinguish any other material degradation effects.

Etched Microstructure

Table 3 and Table 4 contain SEM images of the marks and optical images of the etched mark cell cross sections. The SEM images of marks show the basic overview of the mark and the adjacent base material. The optical images of the etched mark cell cross sections show the microstructure of the mark and the adjacent base material.

Note that it is difficult to obtain an etched image without staining within 0.002in. of the cell surface. An edge is typically etched more aggressively than the interior because there is a small separation between the epoxy mount and the edge that allows etchants and rinses to continually weep and cause staining. Sometimes the etched microstructure looks perfect for several seconds and, as the image is taken, the staining occurs. Obtaining an unstained image is particularly difficult for high strength steel. In any of the images, the dark regions near the surface and in the base material are artifacts from the staining due to the nital etchant edge effect. For example, the image of the etched mark cell cross section on steel after garnet blasting in Table 3 has a dark region near the cell surface that is an artifact from the staining. The same image also has a large circular black stain that is an artifact of the etching and not a flaw.

The etched steel had a typical base material microstructure of tempered martensite with uniform laths at random orientations. Note that laths of tempered martensite are barely observable at 500X magnification. The etched aluminum had a typical base material microstructure of heat treated, age hardened, aluminum plate with uniformly elongated grains.

The microstructure for the mark on steel had a shallow heat affected zone approximately 0.001in. thick at the cell surface. The shallow heat affected zone is consistent with a thin, connected layer of untempered martensite that results from very rapid melting, resolidification, and transformation of the steel after the final heat treatment. The steel would easily transform to untempered martensite during the very rapid resolidification. The transition microstructure between the untempered martensite and the tempered martensite was less than approximately 0.0001in. The microstructure for the mark on aluminum had a shallow heat affected zone approximately 0.001in. thick at the cell surface. The shallow heat affected zone is consistent with a thin layer of as cast aluminum that results from very rapid melting and resolidification of aluminum after heat treatment. The transition microstructure between the as cast aluminum and the age hardened aluminum was less than approximately 0.0001in.

For the mark on steel after glass blasting, the microstructure had a shallow heat affected zone approximately 0.0005in. thick at the cell surface. The shallow heat affected zone decreased in thickness, but was not completely removed by the glass blasting. For the mark on steel after garnet blasting, the microstructure did not have a shallow heat affected zone at the cell surface. The base material microstructure of tempered martensite continued up to the cell surface. The shallow heat affected zone for the marks on steel was removed by the garnet blasting. The test data demonstrates that for marks on steel the glass blasting is not aggressive enough to remove the shallow heat affected zone, while the garnet blasting is aggressive enough to remove the shallow heat affected zone. For the mark on aluminum after glass blasting, the microstructure did not have a shallow heat affected zone at the cell surface. The base material microstructure of age hardened uniformly elongated grains continued to the cell surface. Near the rim, the uniformly elongated grains were deformed by the glass blasting. The shallow heat affected zone for the marks on aluminum was removed by the glass blasting.

A heat affected zone is not an acceptable material condition for the surface of a landing gear part. The material in the heat affected zone would be expected to crack and consequently propagate a crack into the base material either immediately under normal loading or prematurely in fatigue loading. For steel, the shallow heat affected zone is consistent with untempered, low toughness, martensite, which would be expected to crack immediately under normal loading. Untempered martensite also has a very high susceptibility to stress corrosion cracking. For aluminum, the shallow heat affected zone is consistent with as cast, low strength, aluminum which would be expected to crack prematurely under normal fatigue loading.

Problematic microstructure features were found for the deep laser engrave mark. The problematic microstructure features were shallow heat affected zones approximately 0.001in thick at the cell surface. For the marks with the shallow heat affected zone, an equivalent controlled flaw size could be considered the mark cell dimensions plus 0.001in. The shallow heat affected zone is not a significant increase for the equivalent controlled flaw size, but it is a significant and problematic microstructure feature for crack initiation. No problematic microstructure features were found for the deep laser engrave mark on steel after garnet blasting or for the deep laser engrave mark on aluminum after glass blasting. For the marks without the shallow heat affected zone, an equivalent controlled flaw size could be considered the mark cell dimensions. The marks without a shallow heat affected zone: provide an acceptable material condition for the surface of a landing gear part; are expected to have similar fatigue life and stress corrosion cracking resistance as vibropeen marks or steel stamp marks with equivalent depths; and therefore provide an acceptable controlled flaw for landing gear applications.

Further mark and material characterization testing, such as fatigue testing or stress corrosion cracking, would be required: to determine the severity of the problematic microstructure features of the mark; to determine the severity of the inherent controlled flaw size of the mark; to determine if there are any problems with the mark that were not detected by the geometry characterization and the microstructure characterization; or to provide test data to demonstrate that a shallow heat affected zone for a mark on a landing gear marking surface may be an acceptable material condition. The further testing should be conducted to confirm that the garnet blasting completely removes the shallow heat affected zone for steel, and to confirm that the glass blasting completely removes the shallow heat affected zone for aluminum. The further testing would determine if the deep laser engrave DPM process degrades the material in a subtle manner or if the deep laser engrave DPM process followed by an abrasive blasting process provides an acceptable microstructure as the test data indicates.

Table 1: Summary of Mark Depth Relative to Coupon Surface
S2A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment
A2A: 7075-T73 Aluminum Marked After Heat Treatment

Coupon		Mark	Dial Gage Individual (in)	Dial Gage Average (in)	SEM Image / Software Individual (in (μm))	SEM Image / Software Average (in)
S2A	-1	Deep Laser Engrave	0.0090 0.0090 0.0095	0.009	0.0069 (176) 0.0078 (198) 0.0080 (204)	0.008
	-2	Deep Laser Engrave After Glass Blast	0.0085 0.0090 0.0090	0.009	0.0091 (231) 0.0092 (234) 0.0087 (221)	0.009
	-3	Deep Laser Engrave After Garnet Blast	0.0085 0.0090 0.0085	0.009	0.0096 (243) 0.0091 (230) 0.0088 (224)	0.009
A2A	-1	Deep Laser Engrave	0.0070 0.0075 0.0070	0.007	0.0102 (258) 0.0101 (256) 0.0102 (259)	0.010
	-2	Deep Laser Engrave After Glass Blast	0.0070 0.0070 0.0075	0.007	0.0086 (220) 0.0086 (220) 0.0086 (220)	0.009

Table 2: Summary of Mark Microhardness Data at Depths Less than 0.005in. from the Cell Surface
S2A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment
A2A: 7075-T73 Aluminum Marked After Heat Treatment

Coupon		**Mark**	**Diamond Pyramid Hardness** DPH - (kg/mm^2) Average ± Standard Deviation	**Percent Change**	**Hardening Softening**
S2A		Material	593.7 ± 3.6	**	**
	-1	Deep Laser- Engrave	523.0 ± 71.7	-11.9%	Minor Softening
	-2	Deep Laser Engrave After Glass Blast	591.4 ± 2.2	-0.4%	No Change
	-3	Deep Laser Engrave After Garnet Blast	592.4 ± 3.7	-0.2%	No Change
A2A		Material	156.9 ± 5.0	**	**
	-1	Deep Laser- Engrave	155.0 ± 2.3	-1.2%	No Change
	-2	Deep Laser Engrave After Glass Blast	148.3 ± 17.2	-5.5%	Minor Softening

Figure 2: Microhardness Data for Coupon S2A
S2A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment

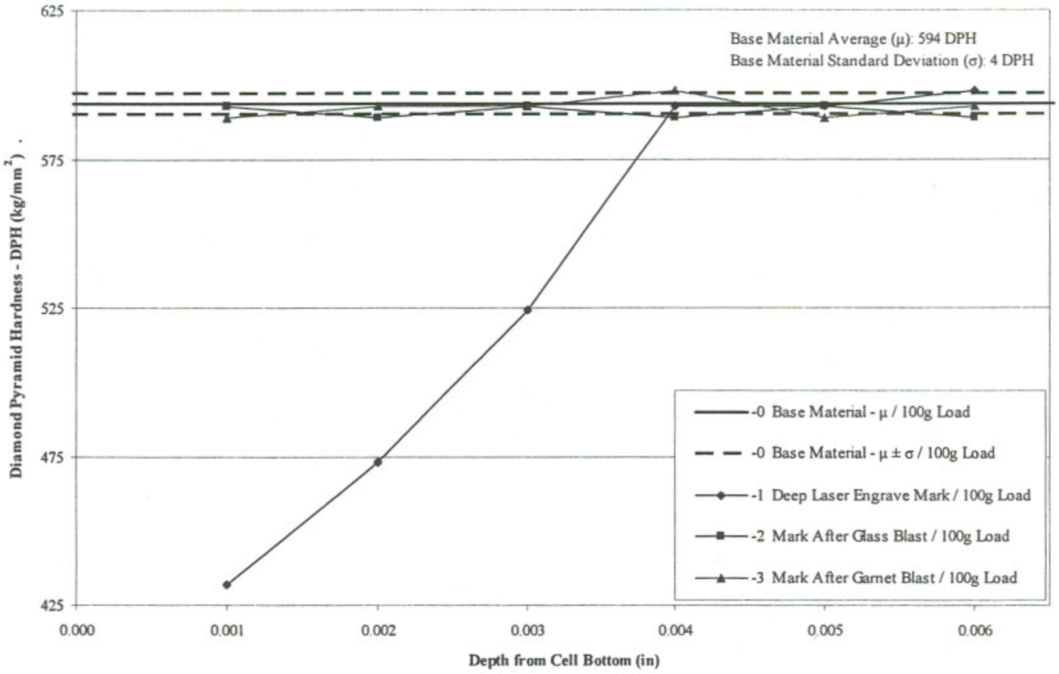


Figure 3: Microhardness Data for Coupon A2A
A2A: 7075-T73 Aluminum Marked After Heat Treatment

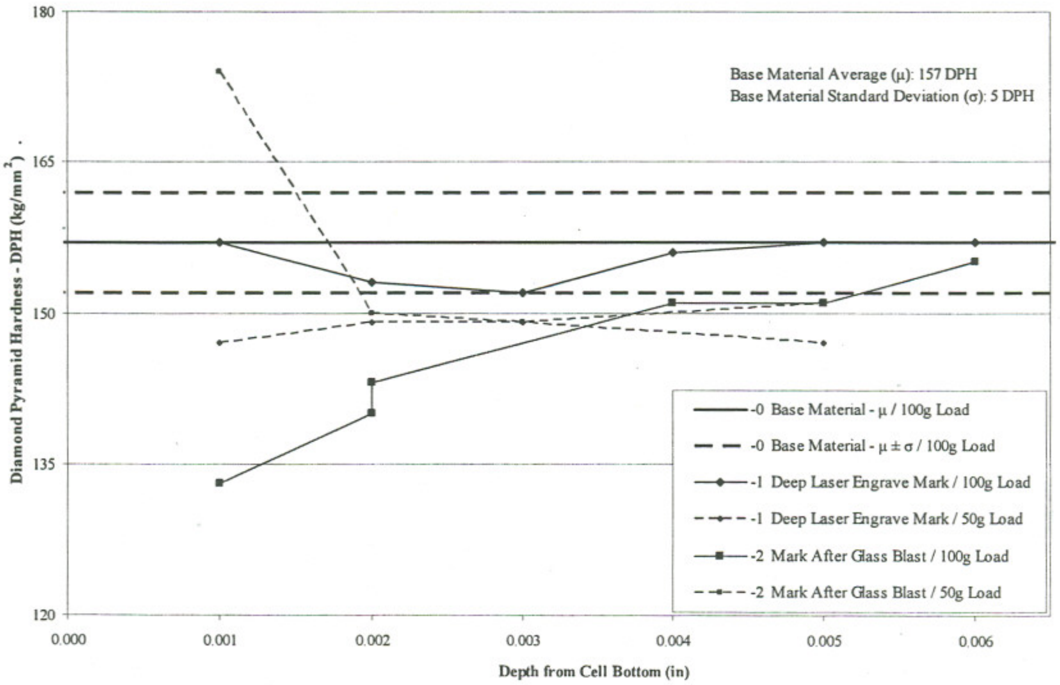
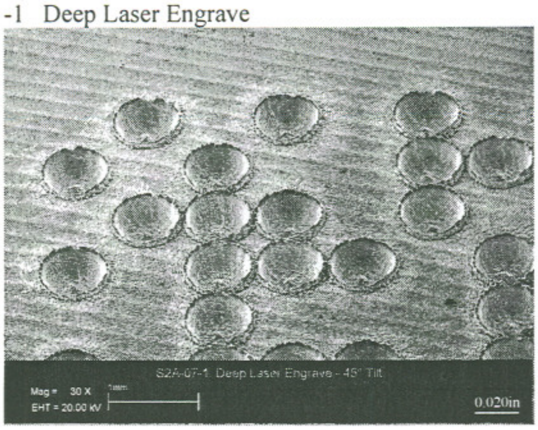
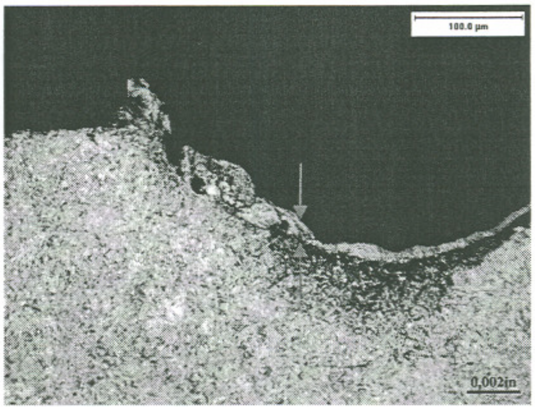


Table 3: Images of Marks on Coupon S2A
S2A: 4340 Steel (260 ksi UTS) Marked After Heat Treatment

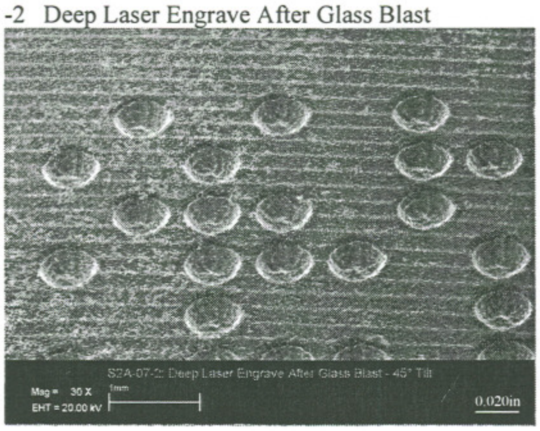
SEM Image of Mark 45° Tilt	Optical Image of Mark Cross Section Etched Microstructure

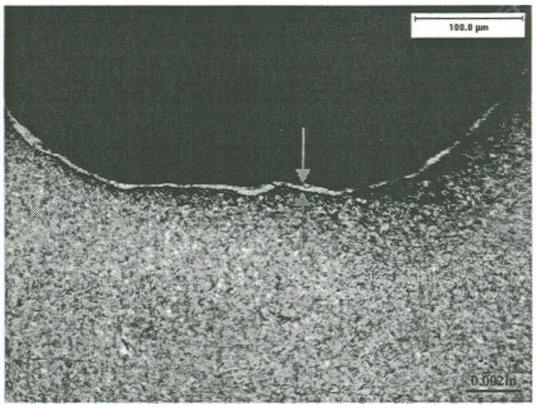
-1 Deep Laser Engrave



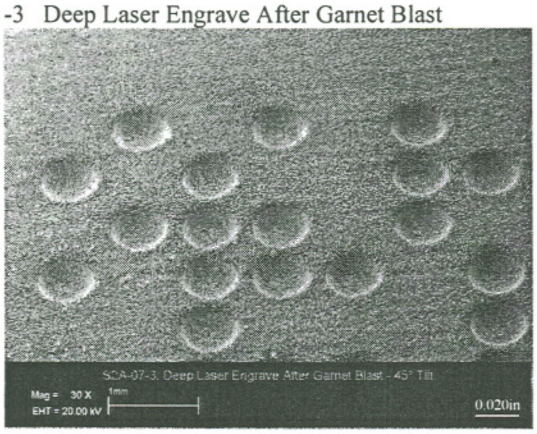


-2 Deep Laser Engrave After Glass Blast





-3 Deep Laser Engrave After Garnet Blast



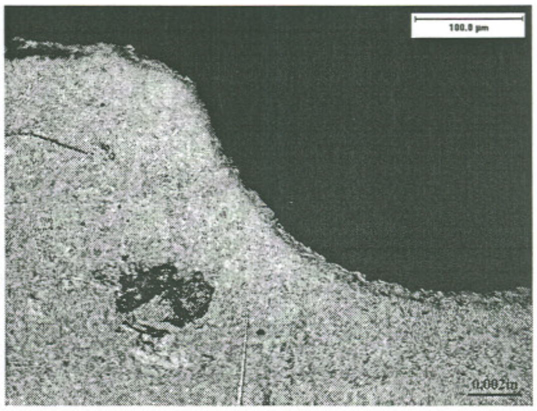
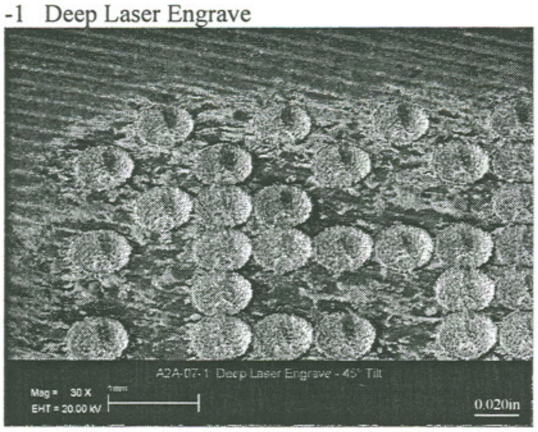
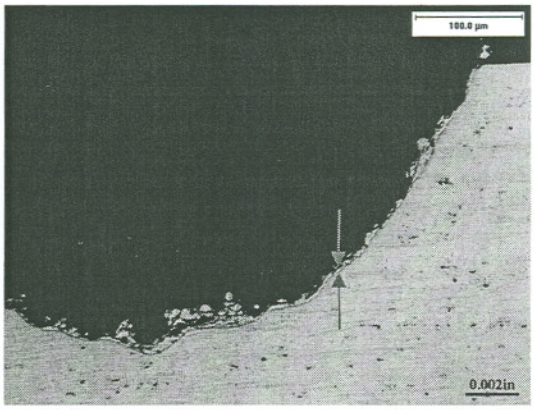


Table 4: Images of Marks on Coupon A2A
A2A: 7075-T73 Aluminum Marked After Heat Treatment

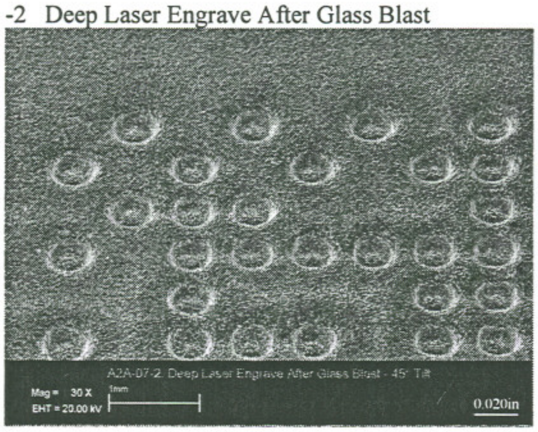
SEM Image of Mark 45° Tilt	Optical Image of Mark Cross Section Etched Microstructure

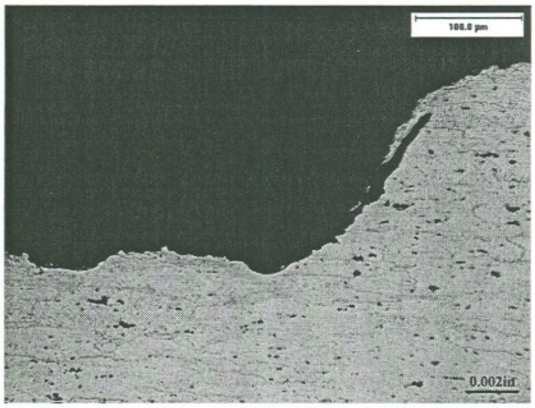
-1 Deep Laser Engrave





-2 Deep Laser Engrave After Glass Blast





CONCLUSIONS

The microscopy test program was conducted for geometry characterization and microstructure characterization of machine readable marks that are applied with the deep laser engrave DPM process. The test program was to determine if the deep laser engrave marks have problematic geometry features or problematic microstructure features that would degrade the material properties of a part, and to determine if it is technically possible to remove the shallow heat affected zone from deep laser engrave marks with an abrasive blasting process. The test program evaluated marks on high strength steel and high strength aluminum.

The geometry characterization provided a basic overview of the marks and identified microscopic features consistent with the deep laser engrave DPM process. The geometry characterization identified no problematic features and a robust mark cell shape with corner radii, tapered sides, and spacing. No evidence of micro cracking in the base material was found for any of the marks.

The microhardness characterization identified minor softening for marks on steel, and no minor softening or minor hardening for marks on aluminum. The microhardness characterization identified no minor softening or minor hardening for marks on steel or for marks on aluminum after garnet blasting or glass blasting.

The etched microstructures identified problematic microstructure features for the mark. The problematic microstructure features were shallow heat affected zones approximately 0.001in thick. The etched microstructures identified no problematic microstructure features for the mark on steel after garnet blasting or for the mark on aluminum after glass blasting.

The geometry characterization and the microstructure characterization provide consistent data that demonstrate: that the deep laser engraving DPM process produces a shallow heat affected zone; and that for marks on steel, garnet blasting removes the shallow heat affected zone; and that for marks on aluminum, glass blasting removes the shallow heat affected zone. The test data demonstrates that it is technically possible to remove the shallow heat affected zone from the deep laser engraving DPM process with an abrasive blasting process. Based on the geometry characterization and the microstructure characterization, the marks on steel after garnet blasting and the marks on aluminum after glass blasting provide an acceptable controlled flaw for landing gear applications.

Further mark and material characterization testing, such as fatigue testing or stress corrosion cracking, would be required: to determine the severity of the problematic microstructure features of the mark; to determine the severity of the inherent controlled flaw size of the mark; to determine if there are any problems with the mark that were not detected by the geometry characterization and the microstructure characterization; or to provide test data to demonstrate that a shallow heat affected zone for a mark on a landing gear marking surface may be an acceptable material condition.

RECOMMENDATIONS

Based on the test data, it is recommended to pursue further development and testing of the deep laser engrave marks.

The test data demonstrated that it is technically possible to remove the shallow heat affected zone from the marks with abrasive blasting processes. However, the further development and testing to define process controls for the abrasive blasting processes is recommended. Further development and testing should determine the minimum surface coverage or the minimum dwell time to effectively and consistently remove the shallow heat affected zone and the associated process controls. This would also reduce mark and/or surface wear. Further development and testing should also evaluate methods to further reduce or eliminate the heat affected zone. For example, a bake at 375°F±25°F following the DPM process and the abrasive blasting process for steel could ensure that any untempered martensite is tempered to a satisfactory state. Also, for example, several surface improvement processes exist that can create a deep compressive residual stress on a surface. Applying a surface improvement process to the marking surface prior to marking may reduce or eliminate any potential fatigue or stress corrosion cracking problems.

For a complete mark and material characterization, it is recommended to conduct fatigue testing and stress corrosion cracking (SCC) testing. The testing should determine: the severity of the problematic microstructure features of the mark; the severity of the inherent controlled flaw size of the mark; if there are any problems with the mark that were not detected by the geometry characterization and the microstructure characterization; or if a shallow heat affected zone for a mark on a landing gear marking surface may be an acceptable material condition. The testing would likely require a significant development effort. It would likely include testing marks on standard coupons to estimate the reduction in fatigue life or SCC resistance at a specific stress level. The testing would likely include unmarked coupons, marked coupons, marked and blasted coupons. The marked coupons would likely include vibropeen marks and deep laser engrave marks for a comparison. The testing would also likely include coupons, machine notched coupons, deep laser engrave notched coupons, machine notched and blasted coupons, and deep laser engrave notched and blasted coupons. A comparison of the coupon test data with landing gear part specific stress analysis data would be required to determine a suitable mark location. Full scale testing of the landing gear parts or assemblies may be required to validate the determination of a suitable mark location from the coupon test data and the landing gear part specific stress analysis. This level of testing would qualify the mark and the mark location for the landing gear parts or assemblies.

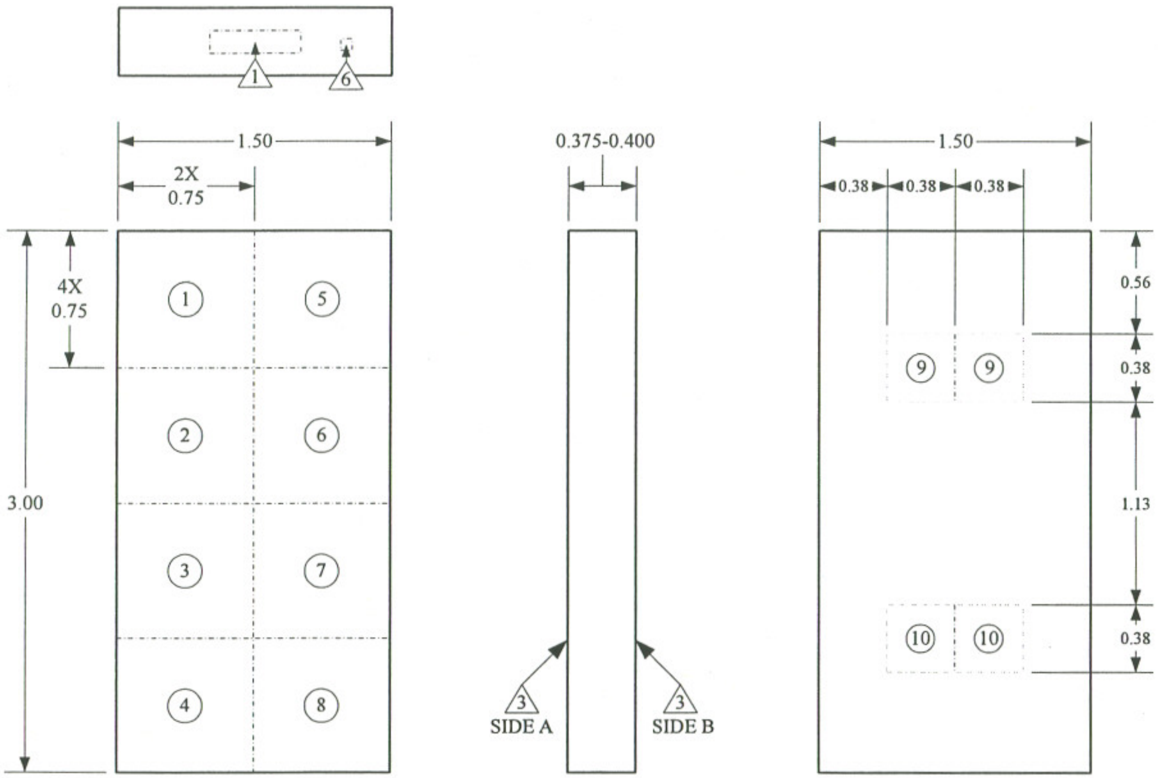
APPENDIX A
COUPON DRAWINGS

COUPON S2A

COUPON S1A REVISION D: HISTORY

New: Unmarked Coupon
A: Unmarked Coupon: Drawing Configuration Change
B: Unmarked Coupon: Material Change
C: Marked Coupon: S2A-01 to S2A-06
D: Marked Coupon: S2A-07 to S2A-10

COUPON



NOTES

1. (△) SERIALIZE THE COUPONS S2A-O1 TO S2A-12 AT NOTED LOCATION USING 025 IMPRESSION STAMP,0.004-0.008 DEEP
2. HEAT TREAT AND PROCESS TO 260-280 KSI ULTIMATE TENSILE STRENGTH PER AMS-H-6875, MAXIMUM ALLOWABLE DECARBURIZATION 0.003
3. (△) 0.025 $\sqrt{}$ 125/64 M BEFORE 2, $\sqrt{}$ 125/64 M AFTER 2
4. BREAK ALL SHARP EDGES 0.005-0.015
5. FLUORESCENT MAGNETIC PARTICLE INSPECT PER ASTM E1444
6. (△) FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM ROCKWELL HARDNESS C TEST PER ASTM A370 AT NOTED LOCATION
7. FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM SURFACE ROUGHNESS MEASUREMENT PER ASME B46.1

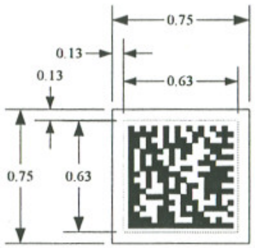
(1) – (10) i) FOR COUPONS S2A-01 TO S2A-06: MARK WITH DATA MATRIX™ SYMBOLS PER TABLE I REQUIREMENTS
ii) FOR COUPONS S2A-07 TO S2A-10: MARK WITH DATA MATRIX™ SYMBOLS PER TABLE II REQUREMENTS

ALGLE PROGRAM (ALGLE logo)	TITLE COUPON	DRAWING NUMBER S2A	REVISION D	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 4340 PER AMS 6415	DATE 2/28/03	SHEET 1 OF 3	SCALE NOT TO SCALE		CHECKED FRANK ZUECH

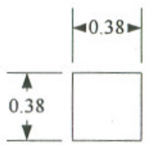
TABLE I: DATA MATRIX™ REQUIREMENTS

1. DOT PEEN MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
2. LASERSHOT™ PEEN MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
3. MICRO-MILL MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.024-0.032 DEEP
4. LASER BOND MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
5. LASER ETCH MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
6. GAS ASSIST LASER ETCH (GALE) MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
7. LASER ENGRAVE MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
8. LASER INDUCE SURFACE IMPROVEMENT (LISI) MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
9. VIBRA-ETCH MARK IN DETAIL I.B PER OO-ALC/LITP PROCEDURE (NOT A MACHINE READABLE MARK)
10. IMPRESSION STAMP MARK IN DETAIL I.B PER OO-ALC/LITP PROCEDURE (NOT A MACHINE READABLE MARK)

DETAIL I.A*



DETAIL I.B*



	MARK DATA
1	XXXXXXXXXXXXXXXXXXX1
2	XXXXXXXXXXXXXXXXXXX2
3	XXXXXXXXXXXXXXXXXXX3
4	XXXXXXXXXXXXXXXXXXX4
5	XXXXXXXXXXXXXXXXXXX5
6	XXXXXXXXXXXXXXXXXXX6
7	XXXXXXXXXXXXXXXXXXX7
8	XXXXXXXXXXXXXXXXXXX8
9	ALPHANUMERIC CHARACTER
10	ALPHANUMERIC CHARACTER

*DIMENSIONS INDICATE THE MAXIMUM ALLOWABLE AREA FOR MARKING

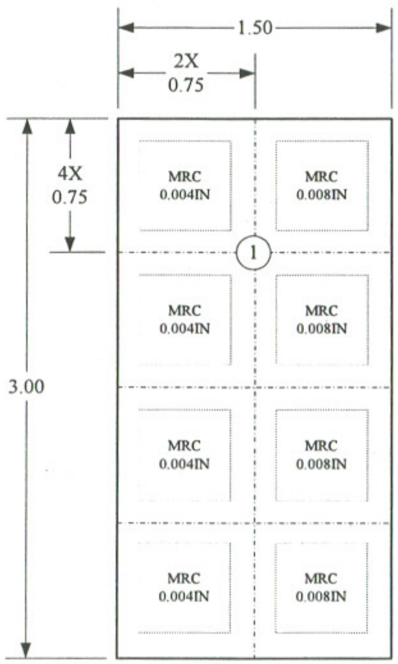
ALGLE PROGRAM	TITLE: COUPON	DRAWING NUMBER: S2A	REVISION: D	DIMENSIONS: ALL DIMENSIONS IN INCHES	TOLERANCES: UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN: JOHN COATES
DPM EVALUATION	MATERIAL 4340 PER AMS 6415	DATE: 2/28/03	SHEET: 2 OF 3	SCALE: NOT TO SCALE		CHECKED: FRANK ZUECH

TABLE II: MARK REQUIREMENTS

(1) DEEP LASER ENGRAVE MARKS IN DETAIL II PER NASA-HDBK-6003 (P027)

(2) – (10) NOT APPLICABLE

DETAIL II: FIGURE

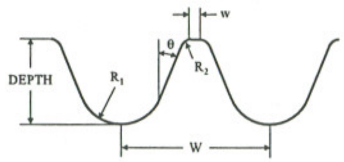


DETAIL II: NOTES AND CELL DETAIL

III.1 LINES AND BOXES INDICATE LOCATIONS FOR MARKS

III.2 MRC / MACHINE READABLE CODE: 18 X 18 DATA MATRIX / DEPTH INDICATED IN BOXES

III.3 MRC CELLS SHALL INCLUDE RADII AND TAPERS AS SHOWN



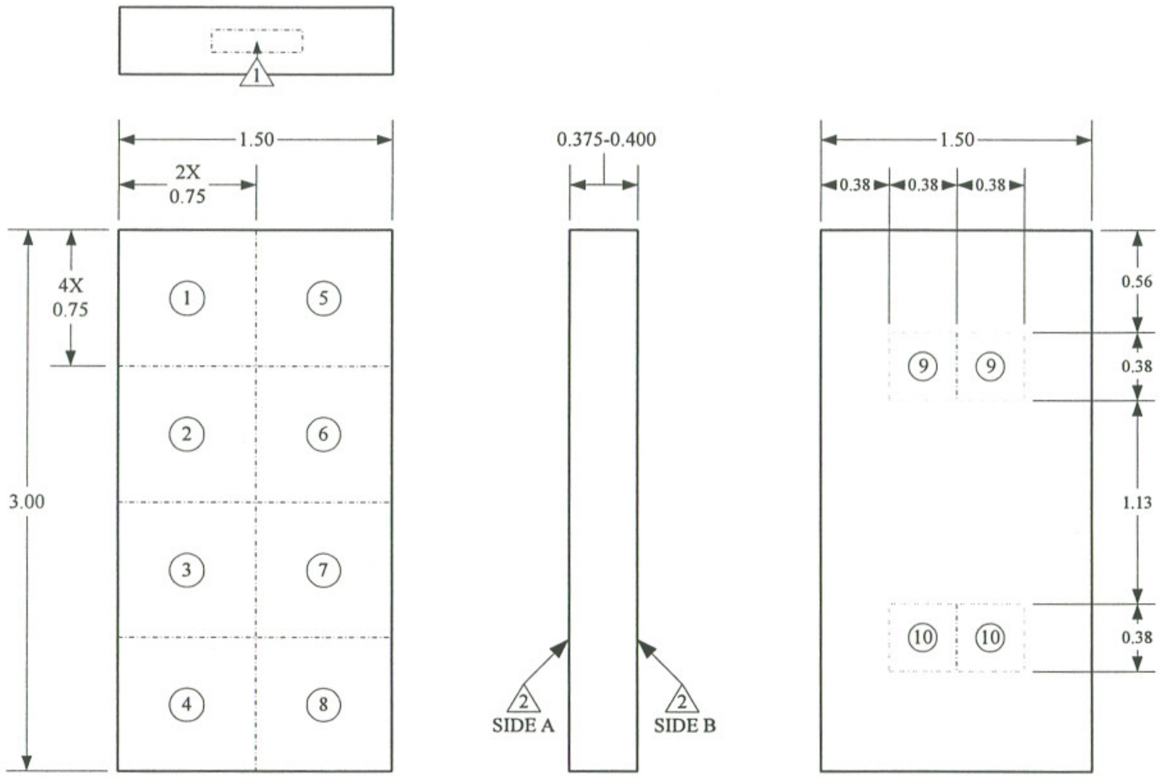
ALGLE PROGRAM	TITLE COUPON	DRAWING NUMBER S2A	REVISION D	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 4340 PER AMS 6415	DATE 2/28/03	SHEET 3 OF 3	SCALE NOT TO SCALE		CHECKED FRANK ZUECH

COUPON A2A

COUPON A1A REVISION D: HISTORY

New: Unmarked Coupon
A: Unmarked Coupon: Drawing Configuration Change
B: Unmarked Coupon: Material Change
C: Marked Coupon: A2A-01 to A2A-06
D: Marked Coupon: A2A-07 to A2A-10

COUPON



NOTES

1. SERIALIZE THE COUPONS A2A-O1 TO A2A-12 AT NOTED LOCATION USING 0.25 MPRESSION STAMP, 0.004-0.008 DEEP
2. 0.025 √ 125/64 M
3. BREAK ALL SHARP EDGES 0.005-0.015
4. FLUORESCENT PENETRANT INSPECT PER ASTM E1417
5. FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM CONDUCTIVITY TESTS PER MIL-STD-1537
6. FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM SURFACE ROUGHNESS MEASUREMENT PER ASME B46.1

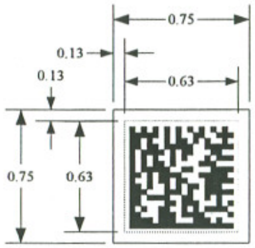
(1) – (10) i) FOR COUPONS A2A-01 TO A2A-06: MARK WITH DATA MATRIX™ SYMBOLS PER TABLE I REQUIREMENTS
ii) FOR COUPONS A2A-07 TO A2A-10: MARK WITH DATA MATRIX™ SYMBOLS PER TABLE II REQUIREMENTS

ALGLE PROGRAM ALGLE	TITLE COUPON	DRAWING NUMBER A2A	REVISION D	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 7075-T7351 PER AMS 4078 (0.5 INCH PLATE)	DATE 2/28/03	SHEET 1 OF 3	SCALE NOT TO SCALE		CHECKED FRANK ZUECH

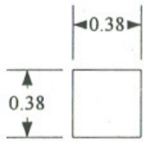
TABLE I: DATA MATRIX™ REQUIREMENTS

1. DOT PEEN MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
2. LASERSHOT™ PEEN MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
3. MICRO-MILL MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.024-0.032 DEEP
4. LASER BOND MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
5. LASER ETCH MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
6. GAS ASSIST LASER ETCH (GALE) MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
7. LASER ENGRAVE MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027), 0.008-0.016 DEEP
8. LASER INDUCE SURFACE IMPROVEMENT (LISI) MARKS IN DETAIL I.A PER NASA-HDBK-6003 (P027)
9. VIBRA-ETCH MARK IN DETAIL I.B PER OO-ALC/LITP PROCEDURE (NOT A MACHINE READABLE MARK)
10. IMPRESSION STAMP MARK IN DETAIL I.B PER OO-ALC/LITP PROCEDURE (NOT A MACHINE READABLE MARK)

DETAIL I.A*



DETAIL I.B*



	MARK DATA
1	XXXXXXXXXXXXXXXXXXX1
2	XXXXXXXXXXXXXXXXXXX2
3	XXXXXXXXXXXXXXXXXXX3
4	XXXXXXXXXXXXXXXXXXX4
5	XXXXXXXXXXXXXXXXXXX5
6	XXXXXXXXXXXXXXXXXXX6
7	XXXXXXXXXXXXXXXXXXX7
8	XXXXXXXXXXXXXXXXXXX8
9	ALPHANUMERIC CHARACTER
10	ALPHANUMERIC CHARACTER

*DIMENSIONS INDICATE THE MAXIMUM ALLOWABLE AREA FOR MARKING

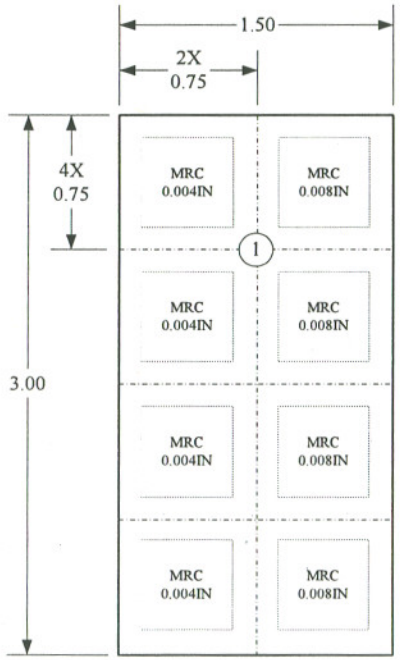
ALGLE PROGRAM	TITLE: COUPON	DRAWING NUMBER: A2A	REVISION: D	DIMENSIONS: ALL DIMENSIONS IN INCHES	TOLERANCES: UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN: JOHN COATES
DPM EVALUATION	MATERIAL 7075-T7351 PER AMS 4078 (0.5 INCH PLATE)	DATE: 2/28/03	SHEET: 2 OF 3	SCALE: NOT TO SCALE		CHECKED: FRANK ZUECH

TABLE II: MARK REQUIREMENTS

(1) DEEP LASER ENGRAVE MARKS IN DETAIL II PER NASA-HDBK-6003 (P027)

(2) – (10) NOT APPLICABLE

DETAIL II: FIGURE

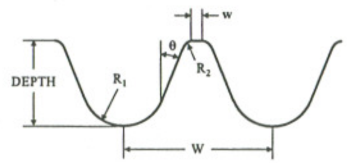


DETAIL II: NOTES AND CELL DETAIL

III.1 LINES AND BOXES INDICATE LOCATIONS FOR MARKS

III.2 MRC / MACHINE READABLE CODE: 18 X 18 DATA MATRIX / DEPTH INDICATED IN BOXES

III.3 MRC CELLS SHALL INCLUDE RADII AND TAPERS AS SHOWN



ALGLE PROGRAM	TITLE COUPON	DRAWING NUMBER A2A	REVISION D	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 7075-T7351 PER AMS 4078 (0.5 INCH PLATE)	DATE 2/28/03	SHEET 3 OF 3	SCALE NOT TO SCALE		CHECKED FRANK ZUECH

APPENDIX B
COUPON MANUFACTURING DOCUMENTATION

COUPON S2A

Northwest Machining and Mfg., Inc.
1957 LANARK STREET • MERIDIAN, IDAHO 83642
PHONE (208) 888-5334 • FAX (208) 888-0917
e-mail nwmm@micron.net

Date: 12/02/00

Job Order Number: 14554

Customer: GENERAL ATOMICS

Part Number: S2A REV: ~~A~~

Description: COUPON B. Srm DEC 0 2 2000

Quantity: 12

Purchase Order Number: H030105

Customer Supplied Material? NO

CERTIFICATION OF CONFORMANCE

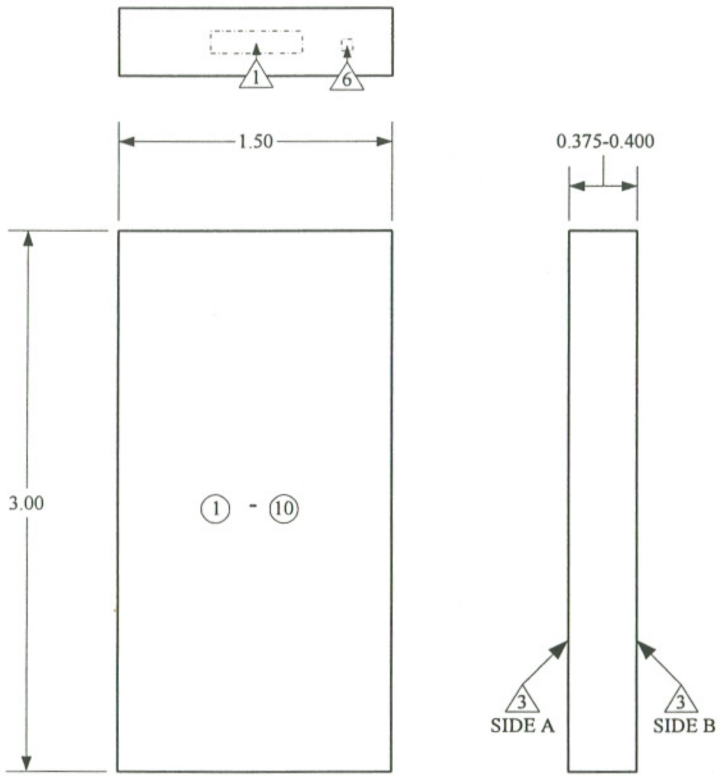
NORTHWEST MACHINING & MFG., INC., DOES HEREBY CERTIFY THAT PARTS MANUFACTURED UNDER THE ABOVE NOTED PURCHASE ORDER WERE PRODUCED AS STIPULATED BY THAT PURCHASE ORDER.

IT IS FURTHER CERTIFIED THAT TEST REPORTS VERIFYING COMPLIANCE WITH DESIGN STANDARDS, MATERIAL CONTROLS, & INSPECTION REQUIREMENTS NOTED ON THE PURCHASE ORDER, ARE ON FILE AND AVAILABLE UPON REQUEST.

SIGNED: Sid Harmon

SID HARMON / (QCM)

COUPON



NOTES

1 (flag) SERIALIZE THE COUPONS S2A-O1 TO S2A-12 AT NOTED LOCATION USING 0.25 IMPRESSION STAMP,0.004-0.008 DEEP

2 HEAT TREAT AND PROCESS TO 260-280 KSI ULTIMATE TENSILE STRENGTH PER AMS-H-6875, MAXIMUM ALLOWABLE DECARBURIZATION 0.003

3 (flag) 0.025 125/64 M BEFORE 2, 125/64 M AFTER 2

4 BREAK ALL SHARP EDGES 0.005-0.015

5 FLUORESCENT MAGNETIC PARTICLE INSPECT PER ASTM E1444

6 (flag) FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM ROCKWELL HARDNESS C TEST PER ASTM A370 AT NOTED LOCATION

7 FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM SURFACE ROUGHNESS MEASUREMENT PER ASME B46.1

(1) – (10) MARK SIDE A WITH DATA MATRIX™ SYMBOLS

ALGLE PROGRAM	TITLE COUPON	DRAWING NUMBER S2A	REVISION B	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 4340 PER AMS 6415	DATE 10/18/00	SHEET 1 OF 1	SCALE NOT TO SCALE		CHECKED FRANK ZUECH

COUPON A2A

Northwest Machining and Mfg., Inc.
1957 LANARK STREET • MERIDIAN, IDAHO 83642
PHONE (208) 888-5334 • FAX (208) 888-0917
e-mail nwmm@micron.net

Date: 12/02/00

Job Order Number: 14557

Customer: GENERAL ATOMICS

Part Number: A2A REV: ~~A~~ B

Description: COUPON DEC 02 2000

Quantity: 12

Purchase Order Number: H030105

Customer Supplied Material? NO

CERTIFICATION OF CONFORMANCE

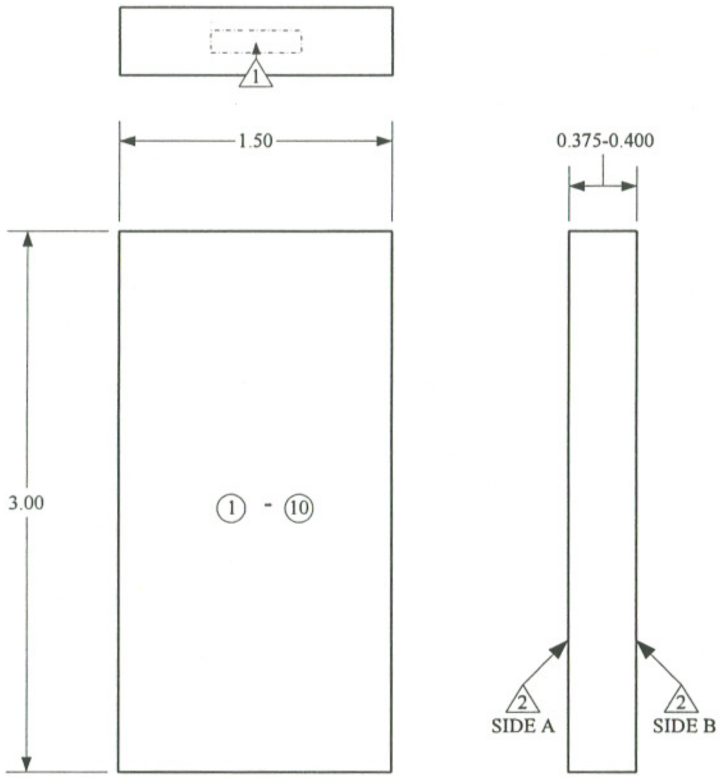
NORTHWEST MACHINING & MFG., INC., DOES HEREBY CERTIFY THAT PARTS MANUFACTURED UNDER THE ABOVE NOTED PURCHASE ORDER WERE PRODUCED AS STIPULATED BY THAT PURCHASE ORDER.

IT IS FURTHER CERTIFIED THAT TEST REPORTS VERIFYING COMPLIANCE WITH DESIGN STANDARDS, MATERIAL CONTROLS, & INSPECTION REQUIREMENTS NOTED ON THE PURCHASE ORDER, ARE ON FILE AND AVAILABLE UPON REQUEST.

SIGNED: Sid Harmon

SID HARMON / (QCM)

COUPON



NOTES

1. SERIALIZE THE COUPONS A2A-01 TO A2A-12 AT NOTED LOCATION USING 0.25 IMPRESSION STAMP, 0.004-0.008 DEEP
2. 0.025 125/64 M
3. BREAK ALL SHARP EDGES 0.005-0.015
4. FLUORESCENT PENETRANT INSPECT PER ASTM E1417
5. FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM CONDUCTIVITY TESTS PER MIL-STD-1537
6. FOR COUPONS WITH EVEN SERIAL NUMBERS: PERFORM SURFACE ROUGHNESS MEASUREMENT PER ASME B46.1

(1) – (10) MARK SIDE A WITH DATA MATRIX™ SYMBOLS

ALGLE PROGRAM (ALGLE)	TITLE COUPON	DRAWING NUMBER A2A	REVISION B	DIMENSIONS ALL DIMENSIONS IN INCHES	TOLERANCES UNLESS OTHERWISE NOTED X.X = ± 0.1 X.XX = ± 0.05 ANGLES = ± 0.5°	DRAWN JOHN COATES
DPM EVALUATION	MATERIAL 7075-T7351 PER AMS 4078 (0.5 INCH PLATE)	DATE 10/18/00	SHEET 1 OF 1	SCALE NOT TO SCALE		CHECKED FRANK ZUECH