



AEROSPACE INFORMATION REPORT

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Landing Gear Manufacturing, Maintenance, Repair, and Overhaul Critical Processes

RATIONALE

This SAE Aerospace Information Report (AIR) provides guidelines and useful references for Critical Processes (CPs) and related lessons learned for structural landing gear systems for an aircraft. It is intended as information only, and should not be used as a mandatory requirement specification.

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1 SCOPE

CPs are a process that is executed on a critical landing gear (or undercarriage) part, assembly or equipment that if performed incorrectly or omitted would cause:

- An operational failure of the aircraft; or
- An unacceptable risk of injury

This document identifies CPs that have either caused operational failure or that can be reasonably expected to cause operational failures based on experience. Note that in the interest of brevity, that this document is not intended to be a definitive listing, only an introduction and a consideration of common processes.

1.1 Purpose

The purpose of this document is to identify landing gear CPs. An additional purpose is to create an information document in easily understandable terms that describes the ways/circumstances in which landing gear integrity may be compromised during manufacture, repair, overhaul, maintenance and operation. This document can be used to educate new suppliers, maintainers, contract compliance monitors, and engineers. This document considered input from major airplane and landing gear system manufacturers as well as relevant industry contributors. Establishment of each CP was supported by real world operational and manufacturing examples. Each CP includes protocol for managing these processes, including definition of appropriate manufacturing, overhaul, and operating parameters.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.2 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AMS2461	Plating, Zinc-Nickel Alloy (12 to 1% Ni)
AMS2649	Etch Inspection of High Strength Steel Parts
AMS-QQ-C-320	Chromium Plating (Electrodeposited)
AMS-QQ-N-290A	Sulfamate Nickel Plating (Electrodeposited)
AMS-QQ-P-416	Plating, Cadmium (Electrodeposited)
AMS-S-13165	Shot Peening of Metal Parts

2.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM E1444	Standard Practice for Magnetic Particle Testing
ASTM F519	Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating Processes and Service Environments

2.4 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

MIL-A-8625F	Military Specification: Anodic Coatings For Aluminum & Aluminum Alloys
MIL-C-26074E	Military Specification: Coatings, Electroless Nickel Requirements
MIL-DTL-5002	Surface Treatments And Inorganic Coatings For Metal Surfaces Of Weapons Systems
MIL-DTL-32648	Performance Specification: Plating, Zinc Nickel, Low Hydrogen Embrittlement, Alkaline Electrodeposited
MIL-I-25135E	Military Specification: Inspection Materials, Penetrant
MIL-STD-410E	Military Standard Nondestructive Testing Personnel Qualification and Certification
MIL-STD-866B	Military Standard: Grinding of Chrome Plated Steel and Steel Parts Heat Treated To 180,000PSI or Over
MIL-STD-867	Temper Etch Inspection
MIL-STD-868B	Department of Defense Standard Practice: Nickel Plating, Low Embrittlement, Electro-deposition
MIL-STD-870C	Department of Defense Standard Practice: Cadmium Plating, Low Hydrogen Embrittlement, Electro-Deposition
MIL-STD-889D	Military Standard: Standard Practice, Galvanic Compatibility of Electrically Conductive Materials
MIL-STD-961C	Military Specifications and Associated Documents, Preparation of MIL-STD-100 Engineering Drawing Practices
MIL-STD-1501	Chromium Plating, Low Embrittlement, Electrodeposition
MIL-STD-1504C	Department of Defense Standard Practice: Abrasive Blasting
QQ-N-290A	Federal Specification: Sulfamate Nickel Plating (Electrodeposited)
QQ-C-320D	Federal Specification: Chromium Plating (Electrodeposited)

2.5 Other Publications

¹ "American Society for Metals (ASM) Metals Reference Book, 3rd Edition, Glossary of Metallurgical Terms and Definitions" ASM International, Materials Park, OH. (2003).

² <https://www.element.com/materials-testing-services/chemical-etching-services/nital-etch#:~:text=Nital%20Etch%2C%20also%20known%20as,of%20the%20part%20in%20question>.

³ <https://www.stresstech.com/knowledge/non-destructive-testing-methods/barkhausen-noise-analysis/#:~:text=Barkhausen%20noise%20analysis%20is%20a,by%20an%20applied%20magnetic%20field.&text=Today%2C%20it%20is%20a%20recognized,and%20heat%20treatment%20defect%20testing.>

⁴ "Hydrogen Embrittlement" in "ASM Metals Reference Book, 3rd Edition, Glossary of Metallurgical Terms and Definitions" ASM International, Materials Park, OH, pp. 48. (2003).

⁵ <https://www.twi-global.com/technical-knowledge/faqs/what-is-hydrogen-embrittlement>.

⁶ J. Huntington, Inst. Metals, 11 (1914), 108.

⁷ D.G. Kolman, "Environmentally Induced Cracking, Solid Metal Embrittlement" in "ASM Handbook, Volume 13A, Corrosion: Fundamentals, Testing and Protection", ASM International, Materials Park, OH, pp. 393-397 (2003).

⁸ D.N. Fager and W.F. Spurr, "Solid cadmium embrittlement: Titanium alloys, Corrosion," 26, 409, (1970).

⁹ <https://onyxinsight.com/wind-turbine-failures-encyclopedia/gear-failures/grinding-burn/>.

¹⁰ <https://grindaix.de/en/magazine/grinding-burn/>.

¹¹ History of Strength of Materials, S. Timoshenko, McGraw-Hill, New York.

¹² Higdon, A., Ohlsen, E.A., Weese, J.A., Riley, W.F., Mechanics of Materials, Fourth Edition, pp. 566 (1985).

¹³ <https://www.aircraftmaintenancestands.com/blog/article/what-is-aircraft-fatigue-and-how-can-fatigue-failure-be-prevented/>.

¹⁴ <https://www.aircraftcompare.com/blog/types-of-aircraft-corrosion/>.

3. BACKGROUND

A significant majority of landing gear components are made from High Strength Steel (HSS) and High Strength Aluminum (HSA) alloys. Components made from these materials generally weigh less and require less volume than components made from lower strength alloys. However, these materials are very sensitive to the following landing gear failure mechanisms:

- Corrosion
- Detrimental surface conditions
- Damage from embrittlement (both hydrogen and liquid metal such as cadmium)
- Damage from overheating
- Improper processing
- Improper packaging and handling
- Improper maintenance/servicing practices

Basic understanding of these factors and their relationship to each other is essential for understanding CPs.

4. UNITED STATES AIR FORCE (USAF) GOVERNMENT/INDUSTRY SURVEY

This document began as a survey and documentation of what the USAF defines as “Safety critical processes” which was approved for unlimited public distribution and then modified by SAE A-5 community of experts. The figures, tables and appendix were provided by the USAF for SAE in this document and are distribution A: Approved for Public Release. The original survey required extensive travel to different industry facilities to ascertain real world operating requirements, design approaches, overhaul methods, and manufacturing practices while focusing on CP/influence and adherence. Specific examples (contributing circumstances and failure details) of non-adherence were captured. Additionally, this survey focused on landing gear systems, which includes landing gear structural components, steering systems, wheels and brakes governed by the SAE A-5 Landing Gear Committee, A-5A Wheels, Brakes, and Skid Control Committee and A-5B Struts, Structures and Couplings Committee.

Survey locations/facilities were identified and adjusted to meet USAF requirements. Prior to the visits, a CP requirements/process survey was prepared that focused on CP that were coordinated with USAF and were used as a guideline for each survey. Each of these critical processes were broken down into critical steps so that a detailed question and answer discussion could occur at each facility. All USAF legacy landing gear processes are defined by the latest revision of the Landing Gear Requirements Document (LGRD) USAF drawing #201416605. Along with Current Military Standards called out in LGRD, SAE documents (Aerospace Material Specification [AMS], Aerospace Information Report [AIR], Aerospace Recommended Practice [ARP], Aerospace Specification [AS]), or other industry specifications such as American National Standards Institute (ANSI) and American Society for Testing and Materials (ASTM) were referred to in order to develop the surveys for each of the CPs.

A baseline approach was used to prepare initial surveys because many commercial entities have proprietary specifications unavailable to USAF at this time. This survey identified industry best practices and developed the following list of major common critical processes that were examined during each site visit where questions were asked, conditions noted, and details recorded immediately following the visits on the survey form (Note: detailed sample survey is included in Appendix A):

4.1 Critical Processes

The following is a list of HSS and HSA landing gear material processes that through their absence or misapplication have caused or contributed significantly to in-service failure of military or commercial landing gear systems:

- **Electroplating:** The process of depositing a metallic coating, such as Cadmium (Cd), Zinc-Nickel (Zn-Ni), Chromium (Cr), and Sulfamate Nickel (Ni) on landing gear components, which is serving as the cathode, for the purpose of applying a wear or anodic corrosion protection coating to enhance the performance and the life of the component.
- **Anodic Coatings (Anodize):** The process of forming a conversion coating on the surface of an HSA landing gear component by anodic oxidation. Type II anodizing is generally for corrosion protection and Type III (hard) anodizing is for wear surfaces.
- **Grinding:** The process of removing base or coated material from an HSS landing gear component using an abrasive grinding wheel or belt.¹
- **Heat Treatment:** The process of heating and cooling an HSS or HSA landing gear component in such a way as to obtain desired conditions or properties, such as Ultimate Tensile Strength (UTS), Yield Strength (YS), Compressive Strength (CS), toughness, etc.¹
- **Thermal Spray:** Is a group of coating processes in which finely divided metallic or nonmetallic materials are deposited in a molten or semi molten condition to form a coating.¹ There are a variety of coatings applied with elevated temperatures in excess of the tempering temperature of substrates. Every coating process must be evaluated and controlled sufficiently to demonstrate that application of these coatings will not induce unacceptable damage to the substrate material. Some common coatings typically utilized on landing gear materials are listed below.
 - **High Velocity Oxygen Fuel (HVOF):** The process uses the heat and pressure generated from the combustion of a liquid or gas fuel mixed to apply thermal spray wear coatings, such as Tungsten Carbide Cobalt (WCCo)/Tungsten Carbide Cobalt Chrome (WCCoCr), on HSS landing gear components. The high particle velocities give very high bond strength, low porosity coatings, that improves or restores the components surface properties or dimensions, thus extending equipment life by significantly increasing erosion and wear resistance, and corrosion protection.

- Flame Spray: Is a thermal spray process which uses the heat generated from combustion of a fuel gas (acetylene, propylene, propane, hydrogen) and oxygen mixture to heat the consumable, either wire or powder. Compressed air/inert gas or a venturi effect, is used to propel the consumable towards the substrate of the landing gear component. This process offers a cost-effective alternative for applying metallic coating in a less demanding environment. However, these coatings can exhibit low bond strength, high oxide content and high porosity.
- Hydrogen Embrittlement (HE) Relief Bake: The process of baking HSS landing gear components in an industrial oven which bakes the hydrogen out of the component after electroplating processes. Typical HE relief baking temperatures for HSS are 375 °F ± 25 °F.
- Residual Stress Relief Bake: Residual stress relief bakes can partially relieve unwanted residual stresses in landing gear component caused from forming during manufacturing, thermal processing, grinding, mishandling, overload event when in service or other damage.
- Shot Peening: Shot peening is a method of cold working HSS or HSA landing gear component in which compressive stresses are induced in the exposed surface layers of a component by the impingement of a stream of shot media, directed at the metal surface and high velocity under controlled conditions.¹
- Maintenance, Servicing, Cleaning, Handling, and Packaging: During the maintenance, manufacturing, repair, overhaul, and servicing of landing gear components the following should be considered:
 - If component was damaged in anyway was engineering contacted and involved in developing the repair procedure (i.e., Material Review Board [MRB])?
 - Due to possible induced residual stresses when components are dropped or mishandled, has a protocol been developed to inspect the components for damage? Is Barkhausen Noise Inspection (BNI) used to detect damage to shot peen layer?
 - What are proper methods for local polishing?
 - Are power tools used? If so, is polished area inspected via temper etch?
 - Is polished area re-shot-peened?
 - How and what protective coating are reapplied?
 - What methods/chemical products are used for cleaning and washing landing gear components?
 - What methods/chemical products are used for maintaining and operating landing gear components?
 - What methods are used to package landing gear components between various processes during manufacturing and overhaul or for final shipping (i.e., what steps were taken to protect components from damage and corrosion)?

4.2 Critical Processes (CP) Inspections

- Non-Destructive Inspections (NDI): NDI, or lack thereof, does not directly cause operational failure. There are, however, historical records of operation failures where inspection fluid, blast media or Cd plating have been discovered on the fracture surfaces of failed landing gear components. This concludes, that if NDI would have been properly performed, operational failure may have been avoided. The following NDI methods are most commonly used for the inspection of landing gear components:
 - Fluorescent Penetrant Inspection (FPI): FPI is a process that can be used on HSA (or other non-magnetic materials) landing gear components which uses a fluorescent liquid that will penetrate a surface opening; after the surface has been wiped clean, the location of any surface flaws may be detected by the fluorescence, under ultraviolet light of a back-seepage of the fluid.¹

- Magnetic Particle Inspection (MPI): MPI is an inspection method that can be used on HSS landing gear components for determining the existence and extent of surface cracks and similar imperfections in ferro-magnetic materials. Finely divided magnetic particles, applied to the magnetized component, are attracted to and outline the pattern of any magnetic – leakage fields created by discontinuities.¹ Shallow subsurface flaws may also be detected using this method.
- Nital Etch (Temper Etch): Nital Etch is an inspection used to determine if overheating has occurred in an HSS landing gear component (after final heat treat) by abusive machining or grinding that will adversely affect the required properties of the component in question. Etching will detect surface variations where softer tempered materials will darken (burn) faster than harder areas on landing gear parts.²
- Barkhausen Noise Inspection (BNI): BNI is an inspection method which involves the measurement of a noise like signal induced in a ferromagnetic material by an applied magnetic field.³ Consequently BNI can be used to determine the degradation of mechanical properties in magnetic materials, such as HSS landing gear components which may be subjected to damage such as cyclic mechanical stresses, grinding, etc. One advantage to BNI is that it can penetrate wear coating such as Cr or HVOF and detect flaws in underlying material.

5. CAUSES OF LANDING GEAR FAILURES

- If the CP are not accomplished per specifications, operation failures have occurred due to the following common failure modes listed in Table 1 below. It should be noted that in the interest of brevity, not all possible failure modes or failure mode combinations were identified in Table 1. Critical processes may cause a complex set of failure modes. This document represents a common sampling and is not intended to encompass every eventuality. For example, abusive grinding can cause burned surface material that may result in a fatigue failure if it is located in a fatigue critical location on the landing gear component, but this is not represented in Table 1 below even though there are documented cases of this occurring.

Table 1 - Critical processes and failure modes

Critical Processes	Common Potential Failure Modes									Remarks: Experience
	HE	EAC	LME/SME	Grind Burns	Arc Burns	Over/Under Temp	Fatigue	SCC	Crev Corr.	
Cd Plating	X	X	X		X					Documented Service failure/mishap
Zn-Ni Plating										No service failure to date
Cr Plating	X			X	X					Spallation causes seal failure, hides grinding burns, fatigue debit, adhesion failures, cracking, corrosion
Ni Plating	X				X					Spallation causes seal failure, fatigue debit
Anodizing							X			
Grinding				X			X			Burns/Thermal damage
Heat Treatment						X	X			Forging flash/burns nucleates cracks, improper can cause fatigue failure
HVOF				X		X				Burns/Thermal damage

Flame Spray						X				Burns/Thermal damage
HE Relief Bake						X				Lack of or improper bake and lack of temperature control
Residual Stress Relief Bake						X				Lack of or improper bake and lack of temperature control
Maintenance / Handling				X		X				Various
FPI*										Failure to identify
MPI*										Failure to identify
BNI*										Failure to identify
Temper Etch*	X									Failure to identify
Shot Peen							X	X	X	Material removal
Note: These are not an all-inclusive list of failure modes that may occur due to critical processes										
*NDI or lack thereof is not directly causal to operational failure.										

5.1 Hydrogen Embrittlement (HE)

A process resulting in a decrease of the toughness or loss of ductility of a metal due to the presence of atomic hydrogen. Typically, for HSS landing gear components, HE results from hydrogen being absorbed by the HSS.⁴

5.1.1 HE Causes

HE can most commonly occur in an HSS landing component the following ways (see Figure 1):

- The use of improper maintenance fluids, cleaners and deicers
- During electroplating (Low Hydrogen Embrittlement (LHE) Cr, Cd, Zn-Ni, Ni, etc.)
- The use of non-porous corrosion preventative platings such as brightened Cd and Zn-Ni or pure Zn (i.e., does not allow hydrogen to bake out after plating)
- Corrosion reactions and cathodic protection (i.e., hydrogen re-embrittlement)

The phenomenon usually becomes significant when it leads to cracking. This happens when sufficient tensile stress is applied or when a stress-intensity factor which exceeds the specific threshold is reached and atomic hydrogen interacts with the metal to induce subcritical crack growth leading to fracture⁴ (see Figures 2 and 3).



Figure 1 - Representative landing gear part with hydrogen embrittlement failure

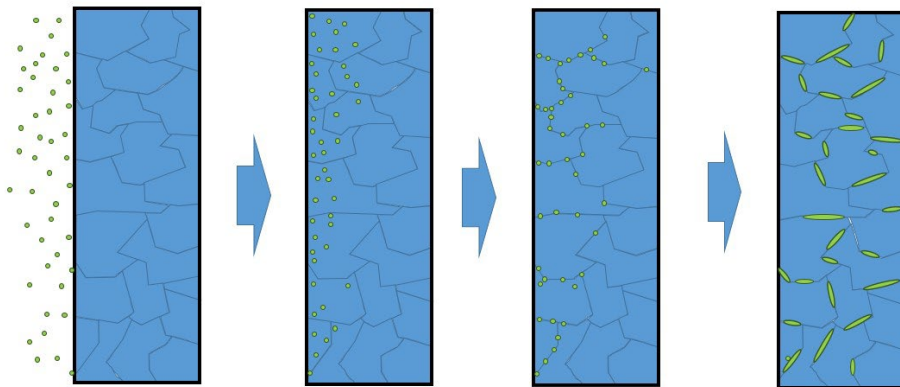


Figure 2 - Notional hydrogen embrittlement process of a metal

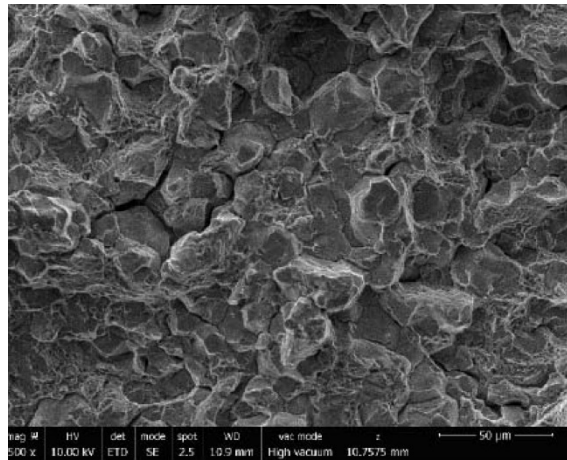


Figure 3 - Embrittlement from the zinc electroplating process

5.1.2 Hydrogen Embrittlement Prevention

The following steps can be taken to avoid hydrogen embrittlement on HSS landing components:

- During manufacturing, repair and overhaul ensure all chemicals, fluids and cleaners used are not hydrogen embrittling. Hydrogen embrittlement susceptibility can be determined using ASTM F519 testing of the representative chemicals or process being utilized. Those substances that enable embrittlement conditions should be appropriately identified and/or controlled by baking components to remove excess free hydrogen (below).
- During flight operational maintenance and cleaning of aircraft components, ensure that maintenance fluids, cleaners and deicers will not cause HE (i.e., do not use low pH [acidic] cleaners such as rust strippers and other aggressive cleaners, disinfectants or deicers).
- For corrosion preventative platings, such as Cd and Zn-Ni on HSS, ensure that the LHE plating solutions (e.g., MIL-STD-870 for Cd and MIL-DTL-32648 for Zn-Ni) are used during the plating process to ensure that plating will be porous and allow the hydrogen to diffuse out during post plating HE relief bake.
- Additionally, for corrosion preventative platings, such as LHE Cd and Zn-Ni, processes utilizing low current density are a concern. These processes should be validated to be non-HE by testing per ASTM F519.
- After electroplating (Cr, Cd, LHE Zn-Ni, Ni, etc.) ensure that all HSS components are baked at 375 to 400 °F (190 to 220 °C) within 4 hours after the electroplating process for 4 to 23 hours depending on the Process Order (PO) requirement. Variations to HE relief bake may be modified by cognizant engineering authority.

During HE relief baking, the hydrogen diffuses out of the HSS component. For applications where there will be hydrogen absorption while a component is in service, the use of lower strength steels and reduction of residual and applied stress are ways to avoid fracture due to hydrogen embrittlement.⁵ There are no non-destructive methods for detecting hydrogen embrittlement in production components. The current process for detecting HE, is to destructively test standard test specimens (ASTM F519), that have been subject to the same CPs as the production components.

5.1.3 Cracking Associated with HE

Cracking associated with hydrogen embrittlement has been given a variety of names depending on the circumstances in which it occurs. Commonly used terms include:

5.1.3.1 Hydrogen Assisted Cracking (HAC) or Hydrogen Stress Cracking (HSC)

Refers to cracking in the absence of a corrosion reaction, which could happen to an HSS landing gear component that was not baked properly after electroplating.⁶