R_{mr} 70%–90% at C_0 = 5%, and C_1 = 0.25 R_z . Note: Unlike chrome, R_a and bearing ratio R_{mr} do not change during service with HVOF applied WC coatings. These parameters were determined in trials utilizing the AMS2452 superfinish method. Caution must be taken if a different approach is taken to achieve the results – a coating can be finished and meet these numerical parameters but not give adequate performance in service.

- Type 2 surfaces provide for limited rotational motion under high-bearing stresses such as axle journals and trunnion pins. The recommended surface finish for Type 2 applications is 8 µinch (0.2 µm) R_a or better. This can be achieved with or without superfinishing.
- Type 3 surfaces provide for high pressure-velocity motion under high-bearing stresses. An example is a bogie beam pivot. The recommended surface finish is 6 µinch (0.15 µm) R_a or better. Superfinishing is preferred, but is not required.

As HVOF is not an appropriate solution for many inner diameters, sulfamate nickel has been used as an alternative. For general purpose nickel plating, AMS2403 [29] can be used. For hard nickel plating, AMS2423 [30] should be used and AMS2424 [31] used when a low-stressed deposit of nickel is desired. In some cases, electroless nickel has been used extensively. One of the advantages of electroless nickel is that it can be plated onto a variety of substrates, including non-conductive materials. Very careful control of the plating process is required to ensure a reliable coating. Electroless nickel is plated in accordance with AMS2404 [32].

During all electrolytic plating operations and electro-chemical processing operations, hydrogen is evolved at the surface of the material being plated. This can lead to hydrogen embrittlement of the plated component. Careful control of the plating process, systematic testing of embrittlement coupons plated alongside the production part, and thorough post-plating baking are required to ensure that parts are not released into service in an embrittled state. Parts suffering from hydrogen embrittlement can fracture rapidly when placed under load.

Other plating techniques are available, and new platings are being developed. Careful and thorough evaluation of new platings is required to understand their impact on the structure, their longevity, and their reliability.

CORROSION PROTECTION COATINGS

Most materials used on landing gear require a coating or treatment to protect against corrosion. Titanium and composites are the rare exceptions, although local coatings may be warranted to protect against galvanic couples if these materials are touching dissimilar materials.

Steels are generally protected with a sacrificial coating of a metal that will corrode in preference to the steel. Historically, this was usually electrolytically deposited cadmium meeting AMS2401 [<u>33</u>] (for high-strength steel parts) or AMS-QQ-P-416 [<u>34</u>]. In some cases, cadmium-titanium plating to AMS2419 [<u>35</u>] or MIL-STD-1500 [<u>36</u>] was used as an alternative to cadmium plating. Due to environmental restrictions in a number of countries, the use of cadmium as a plating is being phased out and replaced with coatings such as alkaline zinc-nickel. Most manufacturers are using proprietary specifications to plate Zn-Ni; a number of existing formulations can be too embrittling for use on landing gears. One formulation which has shown excellent promise and is beginning to be adopted is the Dipsol IZ-C17 formulation, which is an alkaline process plating zinc-13% nickel alloy. A significant amount of investigation has been conducted into possible coatings that are environmentally friendly [<u>37</u>]. An environmentally acceptable plating used historically was ion vapor deposition of aluminum to AMS2427 [<u>38</u>]. As this process requires a suitably sized vacuum chamber for the components, it is not in common use.

Cadmium plating has a relatively low melting temperature, and it is known to embrittle steel in its liquid form. Caution should be used when considering cadmium plating for the axles of braked wheels as high brake temperatures can lead to melting of the coating and a subsequent fracture of the axle. An alternative may be to use zinc-nickel coating or a metallic-ceramic anti-corrosion coating. Care should be taken to ensure that parts coated with cadmium are not in contact with titanium as titanium can be embrittled by cadmium in its solid form. Cadmium is also to be avoided where it can be in contact with hydraulic oils – such as within shock absorbers or hydraulic actuators as it can react with the oil to form a gummy substance.

For aluminum components, the material is typically anodized for additional corrosion resistance, unless electrical conductivity is required, in which case a chemical conversion is utilized. There are several types of anodization, some of which use chromic acid, which contains hexavalent chromium and is being phased out. In replacement of chromic acid anodize, sulfuric acid anodize can be used. Work is ongoing with other anodize formulations, such as tartaric-sulfuric acid anodization or boric-sulfuric acid anodization. The latter two are typically performed in accordance with manufacturers' procedures whereas traditional anodize is conducted in accordance with MIL-A-8625 [39]. Many anodize types are outlined in the standard, including hard anodization, which can be used where the aluminum will be a wear surface. Anodization consumes a portion of the surface layer to form an ordered porous structure of aluminum oxide that is integral to the part. The dimensional change of the aluminum is negligible for most processes, but for hard anodization the total thickness is increased at the expense of a reduction of the amount of aluminum. The porous structure is generally sealed in a subsequent process and additional additives such as polytetrafluoroethylene (PTFE) can be used to seal the anodized layer. Many of the historical sealant processes involved the use of hexavalent chromium and are now being replaced with more environmentally friendly processes. An example is a potassium permanganate sealing process, shown in Figure 12.14.

Where electrical conductivity is required (an anodized layer is not electrically conductive), a chemical conversion coating is used. This coating, often called by its trade

FIGURE 12.14 Anodized and sealed outer cylinder.

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names Alocrom 1200 or Alodine 1200, is performed in accordance with MIL-DTL-5541 [40]. While this coating is not strictly conductive, it is thin enough so as to not significantly increase the electrical resistance.

While corrosion resistant steel is naturally corrosion resistant, it is generally advisable to chemically accelerate the formation of the protective oxide coating on the material before releasing it to service. This process, called passivation, is conducted in accordance with AMS2700 [41] and helps in ensuring the uniformity of the oxide coating on the component.

In some applications, such as the rack and pinion in a nose wheel steering system, it may be desirable to provide some corrosion protection on parts that are working in contact with each other, but are in a greased location. In this case, for steel components, a black oxide coating can be considered in accordance with MIL-DTL-13924 [42]. The coating does not provide a high level of corrosion protection on its own and care should be taken if reliance on the coating is expected.

Materials such as steel and aluminum are typically painted over their corrosion protective coatings. A primer coat is applied that provides most of the corrosion resistance and one or more top coats are applied to seal and protect the primer paint. Many manufacturers utilize their own specifications for paint, but some standard paints that could be considered include MIL-PRF-23377 [43] primer and MIL-PRF-85285 [44] top coat, which meet MIL-PRF-32239 [45].

Sealing between surfaces is typically performed with a corrosion inhibiting sealant such as those meeting MIL-PRF-81733 [46]. The objective of these sealants is to keep fluids from entering crevices, such as between the head of a bushing and the lug against which it is inserted. Judicious use of sealants can avoid the ingress of a corrosive electrolyte and prolong the life of components, especially where faying surfaces are used to maintain electrical conductivity. In some cases, sealants can be applied to large surfaces by spraying or rolling to protect against foreign object damage. Not all sealants resist the range of fluids expected to be seen on aircraft – attention must be paid to the fluid resistance of the selected sealant. In the case of sealants used for foreign object damage, it is customary to apply them over the primer paint coat and then to spray top coat paint over the entire part, including the sealant. With the increasing use of sealants with low quantities of volatile organic compounds, it is important to ensure that components are scrupulously clean before applying sealants to achieve a good bond. In some cases, sealants may require the application of an adhesion promoter to prepare the surface for appropriate adhesion.

Guidance on the development and selection of environmentally compliant coatings for landing gear can be found in document AIR5479B [47].

Inspection

To ensure the integrity of components, a number of nondestructive tests are performed during and after the manufacturing process. During the production of raw materials, ultrasonic inspections are used to ensure the homogeneity of the materials and that no large inclusions, voids, or other defects are found. After heat treatment, conductivity tests are performed on aluminum alloys to confirm that the correct treatment was applied. For other materials, an indentation hardness test is generally performed. Following machining operations, inspections for the presence of cracks are performed. On magnetizable materials, this is generally a magnetic particle inspection while on non-ferrous materials a dye penetrant inspection is formed. In both cases, a fluorescent dye is applied to the part that gravitates to areas of cracks (or in the case of magnetic particle inspection to areas of magnetic field concentration). For some materials, an eddy

current inspection may be performed; eddy current inspection offers a higher probability of detection of smaller cracks than the penetrant methods, but it cannot reasonably cover a large area.

Special processes such as plating operations bring with them a number of dedicated inspections. For many plating operations on steel and ultra-high tensile strength steel, a test for hydrogen embrittlement is generally performed. This test is conducted on specimens treated in the same plating baths as the parts of interest. Grinding operations bring the possibility of excessive heating of the material, and inspections should be conducted to ensure that this frictional heating has not changed the temper of the material; excessive heating of steels leads to local softening, hardening, and the formation of cracks. A temper etch inspection can be performed when the material is exposed. If the material is covered by a coating then a Barkhausen noise inspection can be performed to identify anomalies in the base material; this type of inspection should be systematic following grinding of hard coatings. The intention of nondestructive tests in production is to identify outliers from a normally stable production process and not to select "good" components from a random batch. Efforts should be focused on ensuring that the production means generate high-quality parts with the inspections being in place to identify anomalous parts that may occur.

Document AIR4777 [48] provides an overview of typical inspection methods, and <u>Table 12.5</u> provides a summary of typical industry specifications used for nondestructive evaluation.

A wider array of test techniques are available than those shown in <u>Table 12.5</u>. Specific situations or production techniques may require different inspections (for example, welding may require x-ray inspection). An overview of a large variety of inspection techniques is available in NASA document SP-3079 [50] or in the ASM Handbook Volume 17 [51]. New advancements in inspection technologies include the development of automated data analysis that assists in reducing human error and can provide additional insight into the state of the component (for instance, by providing three-dimensional characterization of internal features).

Every inspection technique has its limits, and it is important to know what a technique is capable of finding when specifying it or relying on it. Nondestructive inspection techniques are typically characterized by their probability of detection. For instance, for crack detection techniques, larger cracks are easier to find than smaller cracks. A specific technique will have a high probability of detecting large cracks and a decreasing probability of finding progressively smaller cracks. Probability of detection data for a variety of inspection techniques, materials, and flaw orientations is provided in the Nondestructive Evaluation Capabilities Data Book [52]. Reliable detection relies on the equipment and preparation as well as human factors: most inspection techniques rely on a human operator to see or interpret the results. Meta-analysis of a number of probability of detection studies has found that the smallest crack that can be detected with 90% certainty with magnetic particle inspection is 2 mm [53] and that for liquid penetrant inspection is 3 mm [54]. A key consideration to keep in mind is that the overriding concern is not the smallest flaw a technique can detect but rather the largest flaw that a technique can miss and release into service. TABLE 12.5 Nondestructive inspection industry specifications.

Inspection type	Specification	Title
General	MIL-HDBK-6870	Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts
	AMS2658	Hardness and Conductivity Inspection of Wrought Aluminum Alloy Parts
	AS3071	Acceptance Criteria – Magnetic Particle, Fluorescent Penetrant, and Contrast Dye Penetrant Inspection
Liquid Penetrant	MIL-HDBK-728/3	Liquid Penetrant Testing
	ASTM E1220	Standard Practice for Visible Penetrant Testing using Solvent-Removable Process
	ASTM E1417	Standard Practice for Liquid Penetrant Testing
	AMS2644	Inspection Material, Penetrant
Magnetic Particle	MIL-HDBK-728/4A	Magnetic Particle Testing
	ASTM E709	Standard Guide for Magnetic Particle Testing
	ASTM E1444	Standard Practice for Magnetic Particle Testing
	AMS2300	Steel Cleanliness, Premium Aircraft Quality, Magnetic Particle Inspection Procedure
	AMS2301	Steel Cleanliness, Aircraft Quality, Magnetic Particle Inspection
	AMS2442	Magnetic Particle Acceptance Criteria for Parts
	AMS2641	Vehicle. Magnetic Particle Inspection Petroleum Base
	AMS3044	Magnetic Particles, Fluorescent, Wet Method, Dry Powder
	AMS3045	Magnetic Particles, Fluorescent, Wet Method, Oil Vehicle, Ready-to-Use
Eddy Current	MIL-HDBK-728/2	Eddy Current Testing
	MIL-STD-1537	Electrical Conductivity Test for Verification of Heat Treatment of Aluminum Alloys, Eddy Current Method
	ASTM E1004	Standard Test Method for Determining Electrical Conductivity using the Electromagnetic (Eddy Current) Method
Ultrasonic	MIL-HDBK-728/6	Ultrasonic Testing
	ASTM B594	Standard Practice for Ultrasonic Inspection of Aluminum Alloy Wrought Products for Aerospace Applications
	ASTM E2375	Standard Practice for Ultrasonic Testing of Wrought Products
	AMS2630	Inspection, Ultrasonic Product over 0.5 inch (12.7 mm) Thick
	AMS-STD-2154	Inspection, Ultrasonic, Wrought Metals, Process for
Hardness <u>*</u>	ASTM E10	Standard Test Method for Brinell Hardness of Metallic Materials
	ASTM E18	Standard Test Method for Rockwell Hardness of Metallic Materials
	ASTM E384	Standard Test Method for Knoop and Vickers Hardness of Materials
Hydrogen Embrittlement	ASTM F519	Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments
Temper Etch	MIL-STD-867C	Temper Etch Inspection
	AMS2649	Etch Inspection of High Strength Steel Parts
Barkhausen Noise	ARP4462	Barkhausen Noise Inspection for Detecting Grinding Burns in High Strength Steel Parts

* Data on the conversion of hardness values between one measurement system and another are provided in ASTM E140-12b [49].

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Corrosion Avoidance

Many of the high-strength materials used in landing gear manufacture are susceptible to corrosion. Indeed, most in-service structural failures of landing gear components arise as a result of corrosion pits, leading to a fatigue crack, or from stress corrosion cracking. For robust through life behavior, landing gear components must be designed with these degradation modes in mind. Ideally, corrosion failure modes are designed out of the system by the careful selection of corrosion resistant materials. However, this type of design is often not possible due either to cost restrictions or to weight and stowage volume concerns. When corrodible materials are selected, they must be appropriately protected against corrosion and careful consideration must be given to avoiding galvanic corrosion cells at the junction of dissimilar materials.

Aluminum and steel must be protected with one or more surface treatments to avoid corrosion. Without protection, or when the protection scheme is breached, significant degradation of the material can occur. An extreme example is shown in Figure 12.15. This aluminum part has succumbed to exfoliation or end grain corrosion. However, not every form of corrosion is as visible. Ultra-high tensile strength steel components will form corrosion pits that can lead to fatigue or stress corrosion failures in the event of a breakdown in surface protection. An example is shown in Figure 12.16 which is typical of a number of landing gear fractures that have occurred throughout the industry. A small corrosion pit forms (usually at a breach in corrosion protective treatment) that leads to a stress corrosion attack (due to sustained tensile loads). Given the relatively low toughness of these materials, a small crack leads to fast fracture of the remaining wall section.

In a similar example on a large aircraft bogie beam [55], the corrosion pit had a total depth of 0.7 mm and a surface diameter of 1.5 mm. A thumbnail shaped area of stress corrosion cracking propagated to a depth of around 6.4 mm prior to fast fracture of the component.

One means of avoiding corrosion is to select corrosion resistant alloys where possible. Typically, this is a choice between titanium alloys, which generally provide high corrosion resistance with no surface treatment required and corrosion resistant steels that have variable corrosion resistance depending on the specific alloy. A listing of typical corrosion resistant steels and their relative corrosion resistance, reproduced from MIL-STD-1568, is shown in Table 12.6. Alloys with a corrosion resistance rating of moderate or higher are generally used



FIGURE 12.15 Highly corroded aluminum door linkage on CF-100 main landing gear.

FIGURE 12.16 Fracture due to corrosion pit and stress corrosion cracking in high tensile strength steel spring.



in landing gear applications with good results. A chemical passivation is typically applied to hasten the formation of the steel's natural protective oxide layer, as well as to make it more uniform. While titanium alloys do not need to be protected against typical corrosive environments, contact with fluorinated or chlorinated compounds must be avoided.

Whenever a design has the potential to trap moisture, a means of drainage should be provided. As the landing gears are stowed in unpressurized zones of the aircraft, a significant difference in atmospheric pressure and temperature can be experienced on

		General corrosion		
Class	Alloy	resistance	Stress corrosion resistance	
Austenitic	301	High	Very high	
	302	High	Very high	
	304	High	Very high	
	310	High	Very high	
	316	Very high	Very high	
	321	High	Very high	
	347	High	Very high	
Martensitic	4,40C	Low to moderate – will develop superficial rust film with atmospheric exposure	Susceptibility varies	
	420		significantly with composition, heat treatment,	
	410			
	416	cxposure		
Precipitation	21-6-9	Moderate	Susceptibility varies significantly with composition, heat treatment, and product form	
hardening	13-8MO	Moderate		
	15-7MO	Moderate		
	14-8MO	Moderate		
	17-4PH	Moderate		
	15-5PH	Moderate		
	AM355	Moderate		
	AM350	Moderate		
	9Ni-4Co-0.20C	Moderate	Very high	
	9Ni-4Co-0.30C	Moderate	Very high	
	9Ni-4Co-0.45C	Moderate	Low	
Other	A286	High	Very high	

TABLE 12.6 Corrosion characteristics of corrosion resistant steels.



FIGURE 12.17 Boeing 737 pins with Cosmoline on interior surfaces.

each flight. This variation in pressure, along with different temperatures and humidity, can lead to moisture being "pumped" into trapped areas. This moisture condenses and accumulates, leading to corrosion. It is preferable to avoid trapped cavities. Where that is not possible, vent holes should be provided such that cavity drains either in the gear down or gear up position – ideally in both. MIL-STD-1568 requires that drain holes be a minimum of 0.375 inches (9.525 mm) in diameter wherever practical.

An additional means to protect against corrosion, especially in partially closed areas, is through the addition of a corrosion preventive compound. These coatings are applied in addition to the normal surface treatments and can act to displace water as well as to alter the local electrolyte chemistry. Historically, a wax like coating called Cosmoline conforming to MIL-C-11796 [56] was utilized by some manufacturers in a number of areas including the interior of pins, as shown in Figure 12.17. Modern corrosion preventive compounds may be formulated to meet MIL-PRF-16173 [57] or MIL-PRF-81309 [58] for the water displacing type. Additional compounds exist that are not expressly formulated to meet military standards. Utilization of some form of corrosion preventive compound can reduce the impact of a corrosive environment and prolong the life of components in service. Attention must be paid that the application of the compound does not block any drainage holes that have been provided.

A good general overview of corrosion processes and lessons learned for corrosion avoidance on aircraft is found in the AGARD Corrosion Handbook [59]. The FAA provides some guidance in Advisory Circular 43-4B [60].

Stress Corrosion Cracking

The phenomenon of stress corrosion cracking (SCC) results from the simultaneous action of tensile stress in the material and exposure to a corrosive environment. The tensile stress can arise due to a standing stress (a tensile stress resulting from the aircraft resting at its static load on the ground) or through residual tensile stresses resulting from manufacturing or in-service overloads or damage. While surface treatments to protect against corrosion will also protect against SCC, this protection is only valid while the surface treatment is intact. Careful design to minimize standing stresses and the selection of materials with better SCC resistance is advised wherever possible to reduce the risk of in-service failures resulting from this mode. Stress corrosion cracking failures are the most prevalent form of landing gear structural failure.

The relative resistance of steels to SCC is shown in <u>Table 12.7</u>, following guidance provided in a document by Marshall Space Flight Center [<u>61</u>]. The relative resistance of aluminum alloys to SCC is documented in ASTM G64 [<u>62</u>] and is tabulated, following MIL-STD-1568, in <u>Table 12.8</u>. The recent trend for aluminum alloys is to use the 7xxx

Alloy	Condition	Resistance
1000 Series	<180 ksi UTS	High
1000 Series	180-200 ksi UTS	Moderate
1000 Series	>200 ksi UTS	Low
Low alloy (4130, 4340, D6AC, etc.)	<180 ksi UTS	High
Low alloy (4130, 4340, D6AC, etc.)	180-200 ksi UTS	Moderate
Low alloy (4130, 4340, D6AC, etc.)	>200 ksi UTS	Low
H-11	>200 ksi UTS	Low
4340M, 300M	All	Low
Music wire (ASTM 228)	Cold drawn	High
1095 spring steel	Tempered	High
HY 80 steel	Tempered	High
HY 130 steel	Tempered	High
HY 140 steel	Tempered	High

 TABLE 12.7
 Rating for resistance to stress corrosion cracking – steel alloys.

TABLE 12.8 Rating for resistance to stress corrosion cracking – aluminum alloys (short transverse grain direction).

Alloy and temper	Rolled plate	Rod and bar	Extruded shapes	Forgings
2014-T6	Low	Low	Low	Low
2024-T3, T4	Low	Low	Low	Low
2024-T6		High		Low
2024-T8	High	Very high	High	Intermediate
2124-T851	High			
2219-T351X, T37	Very high		Very high	Very high
2219-T6	Very high	Very high	Very high	Very high
6061-T6	Very high	Very high	Very high	Very high
7005-T53, T63			Low	Low
7039-T64	Low		Low	
7049-T74	Very high		High	High
7049-T76			Intermediate	
7149-T74			High	High
7050-T74	High		High	High
7050-T76	Intermediate	High	Intermediate	
7075-T6	Low	Low	Low	Low
7075-T736				High
7075-T74	Very high	Very high	Very high	Very high
7075-T6	Intermediate		Intermediate	
7175-T736			High	
7475-T6	Low			
7475-T73	Very high			
7475-T76	Intermediate			

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series in the T73x or T74x condition to minimize the occurrence of stress corrosion. Information for corrosion resistant steels is provided in <u>Table 12.6</u>.

Further guidance on the mechanisms of stress corrosion cracking is provided in NBS Monograph 156 [63]. Specific guidance related to the protection of aircraft structure against SCC is available in Leaflet 7 of DEF STAN 00-970 [64].

Galvanic Corrosion Avoidance

Galvanic corrosion occurs where dissimilar metals are in contact in the presence of an electrolyte containing dissolved oxygen. A galvanic cell, along with an example of corrosion pitting due to galvanic corrosion, is shown in Figure 12.18. Special attention must be paid to ensuring that where dissimilar metals come together in an assembly that they are either very close to each other in terms of galvanic potential or that they are coated with mutually acceptable materials to ensure compatibility. A galvanic series is shown in Figure 12.19, showing the potential difference between a variety of materials. For landing gear service, a potential difference of 0.15 volt between materials is generally acceptable. If the potential difference between adjacent metals is 0.25 volt or greater, than a means of avoiding galvanic corrosion must be employed. While the relative position on the galvanic series is important, it is the current which is developed between adjacent materials that drives the corrosion rate. If the materials are separated by something (such as grease or oil) which avoids the ingress of an electrolyte, then larger galvanic potentials can be accepted; an example is chrome and bronze that have a potential difference around 0.3 volts but which function well in greased landing gear joints.





