Protective surface coatings for aluminum
Tutorial for OPTI 521
By Brian Cranton
November 29, 2010

**1. INTRODUCTION**

Aluminum has beneficial qualities making it a highly desirable mechanical part material. For a metal, it has light weight, good thermal conductivity, electrical conductivity, and good easy of machining. However, it has drawbacks; it quickly oxidizes, wears rapidly, is relatively soft (dings and scratches easily) and can gall. Protective coatings are one means by which the negative aspects of aluminum can be mitigated or eliminated, albeit with consequences resulting from the protective coating choice. Environmental factors that lend themselves to the use of a protective coating include:

* Chemical corrosion[[1]](#footnote-1): Although pure aluminum is highly resistant to chemical corrosion, aluminum alloys may have constituents susceptible to corrosion. Corrosion can be mitigated by using marine grade aluminums, such as 6061; however in situations where other alloys, such as high strength 7075, are desired a protective coating may be appropriate.
* pH based corrosion: In cases of highly acidic or basic exposure, the natural oxide layer may become unstable or be overwhelmed. The US Army Corps of Engineers guidelines put the usable pH range for unprotected bare aluminum around 4.0 to 8.5[[2]](#footnote-2). When the aluminum will be exposed to pH levels differing substantially from a neutral 7.0 for any period of time a protective coating may be appropriate.
* Electrical/dissimilar metal (galvanic) corrosion: In the presence of an electrolyte such as salt water, electrolytic corrosion of aluminum can. Aluminum is quite susceptible to this corrosion type, so much so that it is commonly used as a sacrificial electrode in galvanic environments to protect other parts (the aluminum becomes the path of least resistance and corrodes before other metal parts are affected). In galvanic environments where the aluminum part is intended to survive for a period of time a protective coating may be appropriate.
* Scratch hardness: Bare aluminum does not have very good abrasion resistance, which is a key factor in making it easy to machine (aluminum does not quickly wear cutting tools). This lack of abrasion resistance can be detrimental to the functioning of the aluminum parts; so the application of a protective coating may be appropriate.
* Galling[[3]](#footnote-3): Galling is a surface phenomenon which can occur when two similar metals are slid across each other. Bare aluminum is very ductile, which makes it highly susceptible to galling. In practice, concerns over galling is why (lacking extraordinary circumstances) are bare aluminum parts are rarely screwed directly into each other. Protective coatings can vastly reduce the issues associated with aluminum galling; in particular anodize serves well as a protection against galling.
* Indentation hardness: Indentation hardness is the resistance of a material to permanent deformation when exposed to localized point loading; for example the Hertzian contact load of a spherical ball in a kinematic mount. Protective coatings, such as anodize, can improve the resistance of aluminum parts to permanent deformation resulting from indentation loading.
* Rebound hardness is a function of the elasticity of the surface, and protective coatings can significantly impact this parameter (which is rather complex as it involves the hardness of both objects involved; for example a hard billiard ball against a soft rubber pool table bumper). Rebound hardness can become a matter of concern when aluminum is subject to impact loading, the more rebound the more chatter, and can be adjusted with appropriate use of protective coatings.
* Electrical Conductivity: Pure aluminum is very electrically conductive, but oxidized aluminum (Al2O3) is an excellent electrical insulator. As aluminum starts oxidizing instantly upon exposure to air, its surface electrical resistance can increase rapdily. Protective coatings, particularly chemical films, can be applied to aluminum to prevent oxidation while allowing good surface electrical conductivity.

**2. ANODIZE, PLATING, AND CHEMICAL FILMS**

The three types of protective coatings presented in this section have been grouped together because vendors specializing in these protective coatings typically offer all three; that is the vendor infrastructure for all three of these protective coatings is similar. Usually a vendor of any one of these three is simply referred to as a “plating house”. A handy plating reference chart is made available by a large protective coating company in Massachusetts, AOTCO, the information for which is provided in Appendix A. This chart provides a good summary of many different metal plating methods.

2.1. Anodize

Anodizing is a process by which the surface of the aluminum is artificially oxidized to create a protective coating. Oxidized aluminum is extremely durable and chemically inert, as one could surmise from its relationship to sapphire or aluminum oxide ceramics which are alternative forms of the same chemical structure (Al2O3). Dimensionally anodize can have anywhere from a negligible to upwards of a 0.005” thickness increase effect on the surface of a part. Some flavor of anodize is typically the most appropriate protective coating for aluminum in opto-mechanical applications.

Aluminum anodize is generally specified in accordance with MIL-STD-8625, which defines three basic types; chromic type I, sulfuric type II, and hard type III. These types are distinguished primarily by the thickness of the resulting anodized layer, which increase from type I (0.00002” to 0.00030”), to type II (0.00007” to 0.00100”), to type III (0.00050” to 0.00450”). These types can all be specified with one of two classes; class 1 non-dyed (no pigment added) and class 2 dyed (colored). Thin anodize, type I or type II, is typically used for chemical resistance and moderate increases in surface hardness. These types are soft enough that they do not substantially increase wear on mating parts and these types can be readily machined or drilled through if parts need modification after plating. Type III provides a very durable and hard surface, which can induce extreme wear in moving parts and make part modification difficult. Type III is usually applied to exterior surface of systems to protect against elements while type I or II are applied to interior parts or parts which will operate in benign environments.

Because anodize is porous, anodized surfaces are generally sealed unless specified otherwise by the finish callout. This sealing is usually through either a chemical impregnation or boiling process. Chemical impregnation, which is sometimes referred to as “cold sealing”, is the less expensive of the two options and effectively seals anodize without sacrificing abrasion resistance. By choosing different sealants, additional desired coating effects can be achieved; such as using a Teflon sealer to decrease the resulting part’s coefficient of friction. Unfortunately, chemical impregnation can adversely impact adhesive bond strength. Boiling, which is sometimes referred to as “hot sealing”, does a reasonable job of sealing an anodized surface with only a minor reduction in the abrasion resistance of the surface and a minor decrease in the ability of the finished surface to hold an adhesive bond. Sealing is particularly important for class 2 anodizes which involve dyes, as without sealing the dye can leach out of the anodize pores over time.

Class 2 anodize is typically black, as black is an easy color to obtain and control. Although many other colors are available, a plating house may have difficulty dialing in a specific anodized color, replicating the color, or assuring uniformity of the color over the part. If a specific color is desired, some reference is typically used; either a callout pointing to industry standard color reference chips (such as Pantone) or by providing color chips to the plating house. Color chips typically take the form of a scale bounding the acceptable range of colors rather than a single color chip (e.g. more red than chip 1 but less red than chip 2). Specifying a class 2 non-black color can quickly complicate the finish callout, vendor negotiation, and inspection process.

Anodizing processes use electrodes attached to the aluminum to accelerate the conversion process. These electrodes can cause blemishes and non-uniformities on the part at the location they are attached (racked), so in cases where such blemishes could be problematic finish callouts can specify specific locations for part racking. If the racking location is critical, contacting a plating house early in the design process is suggested. Sometimes it may become appropriate to add a feature to the part whose sole purpose is to act as a racking point.

In situations where it is desired to have both anodized and bare spots on a single part, masking can be specified. Methods of masking can take many forms, such as installing set screws into tapped holes, pushing cork into holes, using a waxy masking material, or using a masking tape. The more complex the geometry of the masking, the more expensive and complex the anodize process can become. In some cases, the easiest solution is to post-machine an anodized part to expose bare aluminum material. It should be remembered that anodized aluminum is more difficult to machine than regular aluminum – and type III hard coat can be particularly problematic to machine.

Anodize can be readily combined with a chemical conversion coating to provide a part with multiple protective coatings without much additional cost. The general process is the aluminum has a chemical film applied, the desired areas of chemical film to remain on the part are masked, the unmasked chemical film is stripped off in a cleaning process preparing the part for anodize, and then the now bare unmasked aluminum is anodized.

Type III hard coat can also result in substantial surface buildup. This buildup can clog the valleys of screw threads, and the hardness of the coating can make clearing these threads with a tap problematic. When dealing with small threads in the #4-40 range or smaller, the anodize buildup can render threads tight or impossible to use. Using a chemical film on the threads or masking them entirely can make a part less expensive and better (in the form of smoother running threads).

Anodizing is a process in which parts are submerged in a liquid bath. Tight spaces, nooks, crannies, and blind holes can be problematic as circulation of the liquid may be restricted in these areas and they may be difficult to clean. It is not uncommon to get anodized parts back with small amounts of either anodize bath liquid or cleaning fluid at the bottom of blind tapped holes, the presence of which only becomes visible when extracted by pressure (positive or vacuum). If contamination is a concern, post-cleaning an anodized part, paying particular attention to blind holes and tight spots, may be appropriate.

Below are some examples of typical anodizing callouts which could be included on a drawing. Anodize is a flexible process and it is common to include special notes to the plating house regarding the anodize application. As with most drawing callouts, it is best not to include something on a drawing without understanding what the callout means; blindly copying notes can be a bad thing.

FINISH: HARD ANODIZE PER MIL-A-8625 TYPE III, CLASS 2
SEALED. THICKNESS: .0003-.00045 BUILD UP PER
SURFACE. (TOTAL THICKNESS .0006-.0009)
COLOR: BLACK

FINISH: HARD ANODIZE PER MIL-A-8625 TYPE III, CLASS 2
SEALED. THICKNESS: .0005-.0007 BUILD UP PER
SURFACE. (TOTAL THICKNESS .001-.0014)
COLOR: BLACK

FINISH: ANODIZE PER MIL-A-8625 TYPE III, CLASS 2, HOT SEALED
COLOR: BLACK
THICKNESS: .0005-.0008 BUILD UP PER SURFACE

FINISH: TEFLON IMPREGNATED HARD COAT ANODIZE PER AMS 2482, TYPE III, CLASS 2.
THICKNESS: 0.0003-0.00045 BUILD-UP PER SURFACE.
(TOTAL THICKNESS .0006-.0009)
COLOR: BLACK

FINISH: ANODIZE PER MIL-A-8625. TYPE III, CLASS 2.
THICKNESS: 0.0003-0.00045 BUILD-UP PER SURFACE.
 (TOTAL THICKNESS .0006-.0009)
COLOR: BLACK

FINISH: ANODIZE PER MIL-A-8625 TYPE II, CLASS 2
COLOR: BLACK
THICKNESS: .0001-.0005 BUILD UP PER SURFACE.

FINISH: SULFURIC ANODIZE PER MIL-A-8625F, TYPE II, CLASS 2
COLOR: BLACK

FINISH: SULFURIC ANODIZE PER MIL-A-8625F, TYPE II, CLASS 1
COLOR: CLEAR

2.2. Nickel plate

There are two basic means of plating aluminum with nickel; with and without electricity (“electrolytic” or “electroless” nickel plating). Both of these processes result in a buildup of material on the part. Nickel is a versatile plating material, and by choosing different forms of nickel plate a wide range of colors, harnesses, and other effects can be achieved. Nickel plating can obscure machining marks on a part, unlike anodize which can show through anodize.

Electrolytic nickel is generally called out in accordance with QQ-N-290 while electroless nickel is called out in accordance with MIL-C-26074. Nickel is commonly used as a barrier layer on aluminum, to prevent adverse effects between the final desired finish and the underlying aluminum alloy. Nickel is not commonly used as the only plating applied to aluminum as other less cumbersome alternatives to achieve similar effects are available.

2.3. Gold plate

As with nickel, gold can be applied with or without electricity. Where feasible applied with electricity is used because it generally results in higher quality plating and because the chemicals involved in electroless gold plating can be particularly nasty (e.g. gold potassium cyanide).

Gold is a flexible plating material with which plating houses across the spectrum of low-to-high quality have tremendous experience. It provides excellent corrosion resistance, resists tarnish, improves solderability, and is good for reducing contact electrical resistance.

Gold plating is not generally applied directly to aluminum because bad phenomenon can result, specifically gold-aluminum intermetallic effects. When gold is desired on aluminum, a barrier layer (almost always nickel) is applied first.

2.4. Chrome

Chrome is not commonly used as a typical aluminum engineering finish, in modern day usage its purpose on aluminum is primarily cosmetic. Its application is controlled by QQ-C-320.

The primary engineering application of chrome is where extremely hard, wear resistant protection is required that functions over a wide range of temperatures. In these applications aluminum is generally not the desired base material as the properties of aluminum nullify the beneficial effects of chrome.

Chrome is becoming increasingly difficult to come by because of the hazardous nature of the chemicals involved in chrome plating. Unless very special circumstances present themselves, chrome is not recommended as a protective coating for aluminum in opto-mechanical applications.

2.5. Alclading

Alclading is a common industrial plating for aluminum alloy parts; it involves plating aluminum alloy parts with pure aluminum (yes, plating aluminum with aluminum). Pure aluminum is highly resistant to corrosion, but the components added to make aluminum alloys are in many cases not. To protect the alloy while keeping the overall part consistent with the properties of aluminum, pure aluminum is deposited over the finished aluminum alloy part. The pure aluminum will then likely need additional protection against oxidation or other detrimental effects that can impair pure aluminum. Alclading is commonly used on light aircraft parts, and generally is post-processed with a protective powder coat of paint.

The pure aluminum plating is somewhat soft and needs to be treated with care. For example, cleaning with a wire brush can scratch off the pure aluminum exposing the alloy underneath to corrosive effects. Unlike most other protective coating processes, when an alclad plating is broken through it can be very difficult to observe because both the plating and substrate are very chemically similar.

2.6. Chemical film

Two types of chemical film are typically applied to aluminum; type IA when maximum protection and good bonding characteristics are desired, and type III when electrical conductivity through the film is important. A typical chemical film callout might be:

 FINISH: CHEMICAL FILM PER MIL-C-5541,
 TYPE I, CLASS 1A
 COLOR: ANY

Chemical films are relatively easy to apply and strip from a part. They have low hardness and help to retain the softness of aluminum. Chemical films make a good field repair protective coating; a can of chemical film can be brought into the field to fill in areas of coating that suffered scratches, damage, or repair work which exposed bare aluminum.

Chemical films are sometimes referred to by brand names, Iridite® or Alodine®.

**3. PAINTING**

There are two common methods of painting aluminum; the traditional prime/paint method and powder coat. Priming and painting involves less specialized equipment, can incorporate numerous colors during the application to create pictures or images, and can be done quickly. But, the results are less durable and uniform than with powder coat. Powder coat results in a very durable coating, but requires some additional equipment especially for large aluminum parts.

For the traditional prime/paint method, the first step is to clean the aluminum surface well. Then, a primer is used to increase the surface energy making the aluminum receptive for paint adhesion. Primers are generally not very durable and the increase in surface energy they bring about is temporary, making it a best practice not to prime until ready to paint and not to use primer without a protective paint layer. In short, primer is not “white paint”. Paint can then be applied in a variety of methods, such as using a bristle brush or air brush. Painting without a primer can be done, however some durability and survivability of the paint will be sacrificed.

Powder coating is usually an electrostatic process where the parts are moved through a chamber containing a fine mist of paint. Electrostatic charge is used to attract the paint to the aluminum. The result is a durable hard paint finish; an example of common aluminum parts which use this process are bicycle frames and school lockers. As would be expected some skill, expertise, and special equipment is required for powder coat; however it is reasonably versatile. For example, school lockers can be painted with this method after being installed in the corridor walls of a school – the equipment can be brought in so that the lockers do not need to be removed. Powder coat is very well suited to volume production.

**4. VAPOR DEPOSITION**

Materials can be vapor deposited or otherwise impregnated onto aluminum in cases where traditional liquid bath plating is inappropriate. Vapor deposition is both more precise and more costly than bath plating so it is normally reserved for unusual or difficult circumstances requiring it. Masking areas of the aluminum from the vapor deposition can be accomplished differently than in a bath method, as a seal is not required, only a mechanical shielding of the areas are to be masked.

**5. ADDITIONAL CONSIDERATIONS**

Successful use of a protective coating requires more than the proper callout of the coating itself. This section reviews topics closely associated with protective coatings.

5.1. Cleaning protective coatings

Some cleaning processes used to remove machining oils and residual from the plating process (such as cleaning the anodizing fluid from the bottom of blind holes) can adversely affect the bonding characteristics of the resulting parts. For example, a common cleaning material by the brand name “Simple Green” is notorious for having detrimental effects on the bond characteristics of surfaces. So if the end use of the aluminum part involves bonding, it could be important to make sure “Simple Green” or equivalent detrimental chemicals are not used to clean the parts.

If the bond characteristics of the resulting surface are important, then the cleaning process employed by the company treating the aluminum surfaces may need to be controlled. An example note that could be included on a drawing is:

USE OF CLEANING AGENTS WHICH LOWER SURFACE ENERGY, OR OTHERWISE
IMPAIR SUBSEQUENT ADHESIVE BONDING ARE NOT TO BE USED. ALL CLEANING
PROCEDURES AND SOLUTIONS ARE TO BE APPROVED BY CUSTOMER.

Use caution applying such a note to a drawing, as the finishing house will likely call and ask for approval of their cleaning process, so only use such a note such as the one above if a person with sufficient knowledge of good cleaning practices will be available to make an intelligent approval or rejection of the process proposed by the vendor. Also, use of such a note may cause some plating house to no-bid the work, as they might have perfectly good but proprietary cleaning processes they do not wish to share.

5.2. Surface finish

Surface texture is sometimes of concern with aluminum parts, so an example of a standard note included on many mechanical drawings is

UNLESS OTHERWISE SPECIFIED, SURFACE
ROUGHNESS SHALL BE 63 MICROINCH OR BETTER.

A 63 µinch finish can have visible structure, and since some protective coatings can show this structure, pretreatment of the part to produce a desired cosmetic finish may be appropriate. For example, where a matte finish is desired, an additional processing step is sometimes callout out for application prior to anodize. A typical note calling out this type of pre-processing would be:

 PREPARE INDICATED SURFACES BY ONE OF THE FOLLOWING PRIOR TO ANODIZING PROCESS.

 1: BEAD BLAST PER FINISH 4.1 OF MIL-STD-171

 2: ETCH IN A SODIUM HYDROXIDE (CAUSTIC) SOLUTION FOR THE NECESSARY
 DURATION TO ENSURE A LUSTERLESS FINISH.

Because the plating can show through surface characteristics of the underlying part, where there is mechanical need to avoid particular characteristics providing additional information to the machine shop about the use of the part can be beneficial. For example, if it is desirable to have machining marks on an o-ring sealing surface along the path of the o-ring and not transverse where they could create leak paths, a typical note to provide this information to a machinist might be

O-RING SEALING SURFACE. NO TRANSVERSE MARKS OR SCRATCHES.

If the o-ring groove is not obvious to the machinist additional information may be needed indicating direction and location. A callout such as this becomes more appropriate the more extreme the requirements become; such as when an important high pressure seal needs to be formed.

5.3. Bimetallic effect of plating aluminum

If a protective coating is being applied to an optical surface, then bimetallic bending effects may need to be considered. In the case when plating with a CTE different from aluminum is used, the aluminum base material can be warped or deformed over temperature excursions. To get a gauge of the extent of the bimetallic bending, consider the basic bimetallic bending relationship for radius of curvature of a bimetallic strip[[4]](#footnote-4):



where

 

 

 

 

 

 

 

Using the above relationship, a Grade A QQ-N-290 nickel coating (0.0016 inches thick) on one side of a 1/8” thick piece of aluminum would result in a radius of curvature of 25meters given a 50°C temperature change. This bending could be eliminated by using symmetry, which involves applying an identical nickel coating to the other side of the aluminum. Unfortunately, in cases where symmetry between the two sides of a piece of aluminum does not exist, such as lightweighted aluminum mirrors that have pockets milled out, a plating can cause substantial adverse effects such as waffling of the front face. It can also be mitigated by using a plating with a CTE similar to the aluminum alloy, such as by alclading.

5.4. Specifying protective coating requirements

Surface treatment of aluminum can result in dimensional changes in the part; sometimes increasing dimensions such as when a coating is applied and sometimes negative when a material conversion or etching/cleaning/abrasion is employed. The end user of the part is generally only concerned with the final dimensions, so it is common to include a note on mechanical drawings such as:

ALL DIMENSIONS APPLY AFTER FINISH

Machine shops, plating houses, and finishers generally will have more expertise in achieving final dimensions than the part designer, so leaving the adjustment of the final dimensions to the part vendors is preferred if they will agree to those terms.

Several additional considerations should be kept in mind when formulating protective coating requirements for aluminum, including:

* Knowing what the desired effect of the protective coating is
* Understanding the protective coating requirements
* The consistency and repeatability of the protective coating
* Ability to inspect the protective coating
* Being able to answer questions about the protective coating
* Number of sources who can provide the protective coating
* Batch and lot considerations

Generally a protective coating is being called out for a reason. These reasons can vary from simply being to fulfill the requirements of a system specification (e.g. customer specifies “all aluminum parts shall be anodized”) to meeting specific technical and cosmetic design criteria. These reasons translate into one or more possible protective coating choices to be specified for parts. Blindly calling out a coating for the sake of having a coating can be undesirable, however having a standard coating can be a reasonable practice. For example, calling out a type II black anodize on all aluminum parts unless otherwise directed.

Once the technical and cosmetic design criteria have been met, considerations such as the consistency and repeatability of the protective coating process needs to be considered. For example, if aluminum parts are specified to have a black anodize protective coating; the resulting parts could have finishes ranging from matte to glossy. That surface finish could vary from batch to batch and vendor to vendor unless additional protective coating requirements are made. A customer’s impression can be affected by appearance; if the customer receives two functionally identical systems, but one is matte finished and the other glossy, they may perceive them to be different functional designs.

Sometimes it may be desirable to control the finish more tightly than is dictated by the technical requirements in order to avoid problems arising from cosmetic differences. Also, having loose tolerances on plating can make failure analysis difficult; sporadic failures which cannot be repeated are some of the most difficult to resolve, and loose specification can make tracking down such failures more difficult than they otherwise might be.

Many characteristics of protective coatings are, by their nature, difficult to inspect. Because the protective coating application can be highly geometry dependent, witness samples are of limited use. Techniques to non-destructively analyze protective coatings can be cumbersome, expensive, and require special expertise. A short list of some plating inspection techniques are ellipsometry, X-ray, or Auger (pronounced “O-J”) electron spectroscopy.

From a practical standpoint, being ready to work with the limitations of the plating house are important. If the plating house calls with a question or request for clarification, not being prepared to provide an answer or clarification can easily throw a wrench into the process (which is frustrating to both the designer and the vendor). Putting extra burden on the vendor, in the form of tight protective coating requirements, inspection requirements, or need to technical assistance, can result in vendors opting out of the work reducing the number of available sources and potentially adversely affecting cost and schedule.

Finally, it is important to keep in mind that almost all protective coating processes are batch processes. The more parts with identical protective coating requirements that are made available at the same time, the less costly and more uniform the resulting parts will be. This batch nature makes the use of standard finish callouts particularly attractive; because if different designers make even small modifications to the note then separate batch lots may be required to apply protective coatings.

5.5. Standards

In the mid-to-late 1900’s the military develop a set of very comprehensive standards for plating and coatings. These standards were so good, and there were so little competing guidelines, that they became industry standards even for non-military use. Over time, the military has decided to get out of the standards business and has passed control over the standards to other outfits such as ASME, ANSI, ASM, ASTM, etc. In many cases the new standards are almost word for word replications of the old military standards.

Although technically the new standards organization standards are the most current, many companies and individuals still refer to the old military standards even in cases where those military standards have been discontinued. A common reason cited for the reluctance to adopt the new standards is that the new standard keepers can charge hundreds of dollars just to see the new standards (you can’t peruse them for free to see if they apply before buying) while the old military standards are freely available in electronic form. The copyright requirements on the new standards can also be quite oppressive, in many cases prohibiting the use of the standards in electronic forms. Large companies sometimes have “external standards” cabinets to hold these legal copies of the standards which is quite cumbersome and discourages use of the new standards by its inconvenience. A well used government site from which military standards can be freely obtained is:

 <https://assist.daps.dla.mil/quicksearch/>

**APPENDIX A: THE AOTCO WALL CHART**

For a couple of decades a plating company in Massachusetts has given away a free plating wall chart that is very commonly used as a plating reference by mechanical engineers. It is the AOTCO wall chart available at:

<http://www.aotco.com/uploads/AotcoMilitarySpecsmostrecent2010.pdf>

1. Perryman, J., “Corrosion Resistance of Aluminum”, Crane Materials International, 2007. <http://www.floodbreak.com/default/Maintenance%20Ops/Aluminum%20corrosion%20paper.pdf> [↑](#footnote-ref-1)
2. Department of the Army, US Army Corp of Engineers, publication No. 1110-2-3401, “Engineering and Design

THERMAL SPRAYING: NEW CONSTRUCTION AND MAINTENANCE”. [↑](#footnote-ref-2)
3. <http://en.wikipedia.org/wiki/Galling> [↑](#footnote-ref-3)
4. J.P. Holman, “Experimental Methods for Engineers”, fifth edition, McGraw-Hill Book Company, pp. 291-292. [↑](#footnote-ref-4)