Surface Engineering of Aluminum and Aluminum Alloys

ALUMINUM OR ALUMINUM ALLOY products often have various types of finishes applied to their surfaces to enhance appearance or improve functional properties. This article discusses the methods employed in the cleaning, finishing, and coating of aluminum.

Abrasive Blast Cleaning

One of the simplest and most effective methods for cleaning aluminum surfaces is by blasting with dry nonmetallic or metallic abrasives. Although this method is normally associated with the cleaning of aluminum castings, it is also used to prepare surfaces of other product forms for subsequent finishes, such as organic coatings. In addition to cleaning, blasting is used to produce a matte texture for decorative purposes.

Abrasive blasting is an efficient means of removing scale, sand, and mold residues from castings. Because castings typically are thick, they generally suffer no distortion from the process. Blast cleaning of parts with relatively thin sections is not recommended, because such parts are readily warped by the compressive stresses that blasting sets up in the surface; coarse abrasives can wear through thin aluminum sections. Typical conditions for dry blasting with silica abrasive are given in Table 1.

Washed silica sand and aluminum oxide are most commonly used for abrasive blast cleaning of aluminum alloys. Steel grit is sometimes used and, because of the fragmenting characteristics of silica, is often preferred. It also has a longer life, which lowers cleaning costs. However, when an aluminum surface is blasted with grit, steel particles become embedded, and unless they are removed by a subsequent chemical treatment, they

will rust and stain the surface. It is good practice to remove particle contamination with a nitric acid pickle to prevent degradation of corrosion resistance. A 20-min soak in 50% nitric acid solution at ambient temperature will dissolve embedded or smeared iron particles, but it will not remove silica or aluminum oxide. When aluminum is blasted with No. 40 or 50 steel grit, a 9.5 mm (3/8 in.) diameter nozzle and air pressure at about 276 kPa (40 psi) are commonly used. Organic materials such as plastic pellets and crushed walnut shells also are used to blast clean aluminum, often for the removal of carbonaceous matter.

Stainless steel shot is sometimes used for cleaning aluminum surfaces. Shot blasting is used as a preliminary operation for developing a surface with a hammered texture. An attractive finish is produced when this textured surface is bright dipped and anodized. In addition, the varying degrees of matte texture that can be produced by blasting offer many decorative possibilities. Blasting is often used to produce the maximum diffuseness of the reflectivity of a surface. For example, aluminum army canteens are blasted as a final finish to reduce glare. Glass bead blasting offers another approach to cleaning and producing diffuse surfaces.

Sandblasting with a fine abrasive produces a fine-grain matte finish on wrought or cast aluminum products. For plaques, spandrels, and related decorative architectural applications, sandblasting the background and polishing or buffing the raised portions of the surface produces an effect known as highlighting.

The matte finish produced by abrasive blasting is highly susceptible to scratching and to staining from fingerprints. Therefore, matte-finish surfaces usually are protected by an anodic coating

or clear lacquer. Anodizing is the more popular protective treatment, because it does not alter the original texture of a surface. Clear lacquers smooth out roughened surfaces and produce various degrees of gloss, which may be undesirable. Anodizing of a blasted aluminum surface results in a gray color because of embedded abrasive particles in the surface. This color frequently is nonuniform because of variations in blasting conditions, such as nozzle-to-work distance, direction or movement of the nozzle, and air pressure.

Blasting conditions can be closely controlled by the use of specially designed equipment. Uniform movement of the work on conveyors, established nozzle movement, constant velocity of the abrasive, and controlled size of grit contribute to better color uniformity of subsequently anodized surfaces.

The nonuniform appearance that results from blasting can be corrected by bleaching prior to anodizing. Bleaching is done by deep etching in a solution of 5% sodium hydroxide at 40 to 65 °C (100 to 150 °F) to remove metal that contains embedded abrasive. Some trial and error may be necessary to determine etching time for specific conditions. If the surface is not etched enough, a mottled appearance may result. Embedded abrasive can also be removed with a solution of nitric acid and fluoride used at room temperature.

Care should be exercised when selecting the aluminum or aluminum alloy to be sandblasted. For example, alloy 1100, which contains 99% Al, provides a transparent anodic finish; alloys rich in manganese, silicon, and copper, on the other hand, are colored when anodized. Alloy segregation can occur in high-magnesium alloys, and pitting will result unless special pretreatments are used. Table 2 lists several typical applications for abrasive blast cleaning of aluminum products, indicating the type and size of abrasive used and typical production rates.

Wet blasting mixes a fine abrasive with water to form a slurry that is forced through nozzles directed at the part. Abrasive grits from 100 to 5000 mesh may be used. Wet blasting is generally employed when a fine-grain matte finish is desired for decorative purposes.

An attractive two-tone finish on appliance trim can be obtained by contrasting a buffed finish with a wet-blasted finish. Aluminum firearm

Table 1 Conditions for abrasive blast cleaning of aluminum products with silica

Grit size	Mesh	Nozzle diameter		Nozzle to work(a)		Air pressure	
		mm	in.	mm	in.	kPa	psi
20-60	Coarse	10-13	3/8-1/2	300-500	12-20	205-620	30-90
40-80	Medium	10-13	3/8-1/2	200-350	8-14	205-620	30-90
100-200	Fine	6-13	1/4-1/2	200-350	8-14	205-515	30-75
Over 200	Very fine	13	1/2	200-300	8-12	310	45

(a) Nozzle approximately 90° to work

Table 2 Applications for abrasive blast cleaning of aluminum products

Automatic rotary equipment with five nozzles was used for blasting of all parts except the cake pan, for which a hand-operated single-nozzle setup was used.

Product	Size		Abrasive		Pieces, h
	mm	in.	Type	Mesh size	
Blasting to prepare for organic coating					
Cake pan	280 by 380 by 51	11 by 15 by 2	Alumina	100	60
Frying pan	250 mm diam	10 in. diam	Alumina	100	260
Griddle	6775 mm^2	10.5 in.^{2}	Alumina	100	225
Sauté pan	200 mm diam	8 in. diam	Alumina	100	250
Blasting for appearance produced					
Army canteen(a)	...	...	Steel	80	420
Cocktail-shaker body(b)	100 mm diam by 180	4 in. diam by 7	Steel	80	375
Tray(b)	300 mm diam	12 in. diam	Steel	80	180

(a) 1 qt army canteen blasted for reduction of light reflectivity. (b) Blasted for decorative effect

Table 3 Conditions for wet blasting of aluminum-base materials

At a nozzle-to-work distance of 75 to 100 mm (3 to 4 in.) and an operating pressure of 550 kPa (80 psi)

Operation	Abrasive	
	Type	Mesh size
Deburr and clean	Alumina	220
Blend and grind	Silica flour	325
Lap and hone	Glass	1000
	Diatomite	625-5000

components and eyeglass parts such as frames and temples often are wet-blasted to produce fine matte finishes. In these applications, anodic coatings, either plain or colored, are used to protect without distorting the intended surface texture.

Typical wet blasting procedures are listed in Table 3. Wet blasting is also used to prepare surfaces for organic or electroplated coatings. Ultrafine glass bead blasting is an alternative to wet blasting.

Barrel Finishing

Barrel finishing is a low-cost method of smoothing sharp edges, imparting a matte finish, and preparing surfaces for anodizing, painting, or plating. Many small aluminum stampings, castings, and machined parts are cleaned, deburred, and burnished by barrel finishing. In most instances, the main objective is deburring and/or burnishing, with cleaning being an accidental benefit of the treatment. Deburring sometimes is the final barrel operation, but more often it is followed by burnishing to obtain a smoother finish or one that is better suited to anodizing or plating. Parts that have only been deburred are often painted. Burnished parts are frequently anodized for protection.

Small aluminum parts are sometimes tumbled dry in media such as pumice and hardwood pegs, hardwood sawdust, or crushed walnut shells to remove burrs and improve the finish. However, this method is relatively inefficient compared to the more widely used wet process.

All aluminum alloys can be safely finished by wet barrel methods. Limitations imposed by workpiece size and shape are essentially the same as for steel and other metals. There are two general areas in which wet barrel finishing of aluminum parts is more critical than in processing similar parts made of steel. First, there is danger of surface contamination by ferrous metals, caused by the use of either a steel barrel or a steel medium. Second, the pH of the compounds is more critical when processing aluminum, because the metal is susceptible to etching by both acids and alkalis, and because gas generated during chemical attack can build up pressure in the barrel and cause serious accidents. Barrels must be vented when processing aluminum. Compounds that are nearly neutral (pH of about 8) are recommended, although some alloys can be

safely processed in compounds having a pH as high as 9.

Barrels used for aluminum are basically the same as those used for processing steel. However, barrels made of steel or cast iron should be lined with rubber or similar material to prevent contamination. A preferred practice is to use specific barrels exclusively for processing aluminum.

Deburring is done by tumbling the work in a nonlubricating compound that contains abrasives. In most instances, media also are used to cushion the workpieces and increase the abrasive action. Synthetic detergents mixed with granite fines or limestone chips are usually preferred as the compound for deburring aluminum; aluminum oxide and silicon carbide are not desirable because they leave a smudge that is difficult to remove. High water levels, completely covering the mass, are used during deburring to assist in maintaining fluidity of the mass and to help prevent the medium from becoming glazed and losing cutting action. Deburring can also be accomplished by using vibratory units with synthetic abrasives.

Barrel burnishing is used to produce a smooth, mirrorlike finish on aluminum parts. Bright dipping immediately prior to burnishing aids in producing desired results. Other preliminary treatments also are helpful in specific instances, particularly for cast aluminum parts. One of these pretreatments entails etching the castings for 20 s in an alkaline solution at 80 °C (180 °F) and then dipping them for 2 to 3 s in a solution consisting of 3 parts by volume nitric acid (36° Bé) and 1 part hydrofluoric acid at 20 to 25 °C (70 to 75 °F).

The principle of barrel burnishing is to cause surface metal to flow, rather than to remove metal from the surface. Burnishing compounds must

Table 4 Conditions for wet barrel finishing of aluminum products

Product	No. of pieces per		No. of pieces per load	Cycle time, min	Barrel speed, rev/min
	kg	lb			
Clean, deburr and brighten(a)					
Percolator spout	60	130	630	20	33
Measuring spoon	20	50	750	20	33
Flame guard	40	90	1500	15	33
Leg	35	80	2700	30	33
Toy spoon	80	180	5000	17	33
Handle	105	225	5800	25	33
Deburr and brighten(b)					
Die cast handles	11	25	600	120	15
Burnish to high gloss(c)					
Die cast housing	5	1	60	45	14

(a) Rubber-lined steel, single-compartment drum, 560 mm (22 in.) diam, 760 mm (30 in.) long. Processing cycle: load drum with medium (20 kg or 50 lb of 3-mm or ⅛-in. steel balls per load), parts, and compound (154 g or 5.5 oz of burnishing soap per load); cover load with water (66 °C or 150 °F); rotate drum for specified time; unload, rinse, separate parts from medium; tumble-dry parts in sawdust for 4 min. (b) Rubber-lined steel, double-compartment drum; each component 740 mm (29 in.) long, 915 mm (36 in.) in diameter. Processing cycle: load deburring compartment with parts, compound (2 kg or 5 lb of burnishing soap), and medium (365 kg or 800 lb of No. 4 granite chips), using hoist; cover load with cold tap water; rotate drum for 1 h; unload, and rinse with cold water; separate parts and medium, and transfer parts to burnishing compartment; add burnishing compound (0.9 kg or 2 lb of burnishing soap) and medium (680 kg or 1500 lb of 3-mm or ⅛-in. steel balls); cover load with water (71 °C or 160 °F) and rotate drum for 1 h; separate parts and medium, and rinse parts in hot water and then in cold water; spin dry in a centrifugal hot-air dryer. (c) Single-compartment drum, 1.5 m (5 ft) long, 1.2 m (4 ft) in diameter. Processing cycle: load drum with parts (parts are fixtured, to prevent scratching), medium (2040 to 2270 kg or 4500 to 5000 lb of steel balls 3, 6, and 8 mm or ⅛, ¼, and ⁵⁄₁₆ in. in diameter, and 2 and 3 mm or ¹⁄₁₆ and ⅛ in. steel diagonals), and compound (5 kg or 12 lb of alkaline burnishing soap. pH 10); cover load with cold tap water; rotate drum for 22½ min in one direction, then 22½ min in reverse direction; rinse and unload; dip-rinse parts, and hand wipe

Table 5 Conditions of belt polishing for bright finishing aluminum die-cast soleplates

Operation	Area polished	Polishing head, No.	Type	Contact wheel Size mm	in.	Hardness, durometer	Belt(a) Size mm	in.	Abrasive mesh size	Life, pieces
1	Side	1, 2	Plain face	50 by 380	2 by 15	60	50 by 3050	2 by 120	280(b)	600
2	Side	3, 4	Plain face	50 by 380	2 by 15	60	50 by 3050	2 by 120	320(b)	600
3	Bottom	5	Serrated(c)	150 by 380	6 by 15	45	150 by 3050	6 by 120	120(b)	1200
4	Bottom	6	Serrated(c)	150 by 380	6 by 15	45	150 by 3050	6 by 120	150(b)	2000
5	Bottom	7	Serrated(c)	150 by 380	6 by 15	45	150 by 3050	6 by 120	220(b)	2000
6	Bottom	8	Serrated(c)	150 by 380	6 by 15	45	150 by 3050	6 by 120	280(b)	2000
7	Bottom	9	Plain face	150 by 380	6 by 15	60	150 by 3050	6 by 120	320(b)	2000
8	Bottom	10	Plain face	150 by 380	6 by 15	60	150 by 3050	6 by 120	320(d)	600

(a) Belt speed for all operations was 35 m/s (6900 sfm). All belts were cloth; bond, resin over glue. (b) Aluminum oxide abrasive. (c) 45° serration, 13 mm ($\frac{1}{2}$ in.) land, 10 mm ($\frac{3}{8}$ in.) groove. (d) Silicon carbide abrasive

have lubricating qualities; soaps made especially for burnishing are usually used and are readily obtainable. Many of them have a pH of about 8, although more acidic materials can be used.

When burnishing aluminum, the pH of the burnishing compound must be closely controlled. This is accomplished by frequent titration of the compound, followed by the addition of small amounts of borax or boric acid as needed. Steel balls and shapes are the most commonly used burnishing media. Several examples of conditions used in barrel finishing applications are detailed in Table 4. Note that deburring and burnishing are sometimes accomplished in a single operation.

Self-tumbling is an effective means of cleaning, deburring, or burnishing small aluminum parts. Procedures for self-tumbling are basically the same as those for other methods of barrel finishing, except that the parts themselves serve as the medium. Compounds for self-tumbling of aluminum should be of nearly neutral pH, and oxides should be removed from the aluminum parts before tumbling. The size and shape of the parts usually determine whether self-tumbling is suitable. Interior surfaces receive little or no action during self-tumbling.

Vibratory finishing is a newer method used for deburring and burnishing metal parts. When applied to aluminum parts, compounds and media are subject to the same restrictions as discussed previously for conventional barrel finishing.

Polishing and Buffing

Because aluminum is more easily worked than many other metals, few aluminum parts require polishing prior to buffing for final finish. In some instances, polishing may be required for the removal of burrs, flash, or surface imperfections. Usually, buffing with a sisal wheel prior to final buffing is sufficient.

Polishing. Most polishing operations can be performed using either belts or setup wheels. Setup wheels may be superior to belts for rough polishing when canvas wheels in a relatively crude setup can be used. For fine polishing work, a specially contoured wheel may be more satisfactory than a belt. Setup wheels have two main disadvantages in comparison with belts: wheels may be costly; and time, skill, and equipment are necessary for setting up

wheels. (The actual time required may be as short as 10 min, but this time is spread over several hours because of intermediate drying steps.) Inventory thus becomes an important factor when several wheels with different types of abrasives or grit sizes are needed. Considerable operator skill is required for wheel polishing, whereas unskilled labor can be used for belt polishing. Flap wheels have been used to replace setup wheels for many applications. The use of flap wheels tends to overcome the above-mentioned disadvantages. Typical conditions for polishing aluminum parts are discussed in the following examples.

The conditions for wheel polishing die cast aluminum soleplates for steam irons are as follows:

Type of polishing wheel	Felt
Setup time	10 min
Wheel speed	1800-2000 rev/min
Lubricant	Tallow grease stick

The medium-hard felt polishing wheel is 350 to 400 mm (14 to 16 in.) in diameter, with a 125 mm (5 in.) face. The surface of the wheel is double coated with 240-mesh alumina abrasive bonded with hide glue. Setup time, spread out over several hours of operation, totals 10 min. The polishing wheel can cover 34 to 43 m/s (6600 to 8400 sfm).

The soleplates are made of alloy 380.0 and the sides are polished to remove holes or other surface defects. Buffing follows to produce the required mirror finish. The polishing conditions given in the list above are based on a production rate of 115 pieces/h per wheel. Each wheel has a service life of 5000 to 6000 pieces.

Table 5 gives the conditions and sequence of operations for belt polishing of die-cast steam-iron soleplates made of aluminum alloy 380.0. Ten polishing heads are used to produce a bright finish on the soleplate sides and bottom.

Buffing. Selection of a buffing procedure depends mainly on cost, because it is usually possible to obtain the desired results by any one of several different methods. For example, depending on the application, hand buffing might call for the use of equipment ranging from simple, light-duty machines to heavy-duty, variable-speed, double-control units. These machines represent a wide range in capital investment.

Automatic buffing requires custom-made machinery or special fixtures on standard machinery. The size and complexity of the machinery are determined by the required production rates and by the size or shape of the workpieces. High production requires more stations, heavier equipment, and more power. The configuration of the part may be so simple that one buff covers the total area to be finished, or it may be so complex as to require the use of many buffs set at angles and advanced toward the workpiece by cam action.

For cut and color work, buffs are bias types with a thread count of 86/93. For severe cutdown, treated cloth is used with the same thread count. The final color work is accomplished using a buff with very little pucker and a low thread count of 64/64 (see Table 6). A number of procedures that have proved successful for high-luster buffing of specific aluminum parts are summarized in Table 6; others are described in the following examples.

Table 7 gives the conditions and sequence of operations for automatic buffing of wrought aluminum frying-pan covers. A specular finish was required. In another case, the sides of die-cast aluminum frying pans made from alloy 360 were buffed to a bright finish by an automatic machine with four buffing heads. The buffing wheel of each head consisted of a 14-ply, 16-spoke sewed bias buff with a 430 mm (17 in.) outside diameter, a 230 mm (9 in.) inside diameter, and a 44 mm (1¾ in.) diameter arbor hole. Wheel speed was 1745 rev/min, equal to 39 m/s (7700 sfm). Each buff was made up of four sections. A liquid buffing compound was applied by one gun per wheel at the rate of 3 g per shot (0.1 oz per shot) for the first wheel, 2.5 g per shot (0.09 oz per shot) for the second and third wheels, and 1 g per shot (0.04 oz per shot) for the fourth wheel. The gun was on for 0.1 s and off for 5 s. The service life of each buffing wheel was 1600 to 2100 pieces.

Die-cast aluminum soleplates for steam irons (Table 8) were buffed to a bright finish on an automatic machine with eight buffing heads. The soleplates were made of alloy 380.0 and were prepolished with 320-mesh grit. A liquid buffing compound was applied by one gun per wheel for the first four heads and by two guns per wheel for the last four heads. The guns were on for 0.12 s and off for 13 s. The service life was 72,000

Table 6 Equipment and operating conditions for high-luster buffing of aluminum products

Product	Size mm	Size in.	Type of buffing machine	Type	Buffing wheel Diameter Overall mm	Overall in.	Center mm	Center in.	Ply mm	Ply in.	Thread count	Wheel speed m/s	Wheel speed sfm	Type of compound	Production, pieces per hour
Biscuit pan	340 by 240	13¼ by 9	Semiautomatic	Bias	360	14	125	5	410	16	86/93	40	8250	Bar	205
Burner ring	75 diam by 20	3 diam by ¾	Continuous rotary(a)	Radial, vented	(b)	(b)	30	1⅛	510	20	64/64	(c)	(c)	Liquid	297
Cake-carrier base	270 diam by 20	11¼ diam by 1³⁄₁₆	Continuous rotary(a)	Bias	Two 360	Two 14	125	5	460	16	86/93	50	9550	Liquid	278
				Bias	Two 330	Two 13	75	3	50	2	64/68	45	8850	Liquid	...
Cake pan	350 by 241 by 65	14 by 9½ by 2½	Hand buffing (handles)	Bias	330	13	75	3	50	2	64/68	40	7650	Bar	438
			Semiautomatic (sides)	Bias	360	14	125	5	410	16	86/93	40	8250	Bar	200
Cake pan	200 by 203 by 50	8 by 8 by 2	Semiautomatic	Bias	360	14	125	5	410	16	86/93	40	8250	Bar	127
Cup	60 diam by 65	2⅜ diam by 2½	Semiautomatic	Bias	360	14	125	5	410	16	86/93	40	8250	Bar	450
Pan bottom	280 by 280	11⅛ square	Semiautomatic	Bias	360	14	125	5	410	16	86/93	40	8250	Bar	106
Pan cover	285 by 285	11¼ square	Semiautomatic(d)	Bias (sides)	360	14	125	5	410	16	86/93	40	8250	Bar	95
				Loose, vented (top)	(e)	(e)	50	2	510	20	64/64	(f)	(f)	Bar	95
Toy pitcher	65 diam by 90	2½ diam by 3½	Continuous rotary(g)	Bias	360	14	125	5	410	16	64/68	50	9550	Liquid	817
Toy tumbler	50 diam by 65	1⅞ diam by 2½	Continuous rotary(g)	Bias	360	14	125	5	410	16	64/68	50	9550	Liquid	864

(a) Five-spindle machine; four buffing heads, one load-unload station. (b) Each of the four wheels used had one 330 mm (13 in.) and three 360 mm (14 in.) sections. (c) For 330 mm (13 in.) section, 45 m/s (8850 sfm); for 360 mm (14 in.), 49 m/s (9550 sfm). (d) Two machines, run by one operator. (e) Buff made up of 360 mm (14 in.), 381 mm (15 in.), and 410 mm (16 in.) sections. (f) 42 m/s (8250 sfm) for 360 mm (14 in.) sections, 45 m/s (8800 sfm) for 380 mm (15 in.) sections, and 48 m/s (9400 sfm) for 410 mm (16 in.) sections. (g) Eight-spindle machine

Table 7 Sequence and conditions of automatic buffing operations for obtaining specular finish on aluminum frying-pan covers

Opera-tion	Area buffed	Buffing head No.	Type	Overall mm	Overall in.	Center mm	Center in.	Arbor hole mm	Arbor hole in.	Ply	Thread count	Den-sity	No. of sec-tions	Speed m/s	Speed sfm	Life, pieces	No. of guns	Cycle, s On	Cycle, s Off	g per shot	oz per shot
1	Sides (4)	1,2,3,4	Bias, air cooled	430	17	180	7	45	1¾	...	86/93	2.4	20	40	7750	40,000	3	0.1	7	0.5	0.02
2	Corners (2)	5,6,7,8	Bias, 20-spoke sewed	430	17	180	7	45	1¾	16	86/93	4	4	40	7750	35,000	1	0.1	7	0.5	0.02
3	Sides (2)	9,10,11,12	Bias, 20-spoke sewed	430	17	180	7	45	1¾	16	86/93	4	4	40	7750	50,000	1	0.1	7	0.5	0.02
4	Sides (2)	13,14,15,16	Bias, 20-spoke sewed	430	17	180	7	45	1¾	16	86/93	4	4	40	7750	35,000	1	0.1	8	0.5	0.02
5	Top	17	Bias, 45° spoke sewed	430	17	180	7	45	1¾	16	86/93	4	15	40	7750	65,000	3	0.1	8	0.2	0.01
6	Top	18	Bias	430	17	180	7	45	1¾	12	86/93	8	18	40	7750	70,000	3	0.1	8	0.2	0.01
7	Top bias	19	Bias	430	17	180	7	45	1¾	12	86/93	8	18	40	7750	70,000	3	0.1	8	0.2	0.01
8	Top bias	20	Bias	410	16	125	5	45	1¾	14	64/68	2	19	37	7300	45,000	3	0.1	8	0.2	0.01
9	Corners (4)	21,22,23,24	Bias	430	17	180	7	45	1¾	12	86/93	8	4	40	7750	65,000	1	0.1	10	0.5	0.02
10	Sides (4)	25,26,27,28	Bias	430	17	180	7	45	1¾	12	86/93	8	4	40	7750	80,000	1	0.1	10	0.5	0.02
11	Top bias	29	Bias	410	16	125	5	45	1¾	14	64/68	2	15	23	4600	80,000	3	0.1	10	0.5	0.02
12	Sides (4)	30,31(b)	Domet flannel	430	17	180	7	70	2¾	20	(d)	(d)	40	20	4000	80,000	6	0.1	11	0.2	0.01
13	Top	32	Domet flannel(c)	430	17	180	7	40	1⅝	32	(d)	(d)	24	25	4900	30,000	3	0.1	11	0.2	0.01
14	Top	33	Domet flannel(c)	430	17	180	7	40	1⅝	32	(d)	(d)	24	18	3550	30,000	3	0.1	11	0.2	0.01

(a) Liquid tripoli compound applied to buffing heads No. 1 through 29; stainless steel buffing compound applied to heads No. 30 through 33. (b) Each head buffs two sides. (c) Domet flannel sections interleaved with 180 mm (7 in.) diam disks of Kraft paper. (d) Inapplicable to flannel buff

pieces for each buff of the first four heads, and 24,000 pieces for each buff of the last four heads.

Satin Finishing

Mechanical satin finishing is an established method for obtaining an attractive surface texture on aluminum hardware items such as knobs, hinges, rosettes, and drawer pulls. Satin finishes are also used for architectural, appliance, and automotive trim. The satin finish results from small, nearly parallel scratches in the metal surface, which give the surface a soft, smooth sheen of lower reflectivity than that of polished or buffed surfaces.

Satin finishes can be applied by fine wire brushing. Other methods use a greaseless abrasive compound in conjunction with a conventional buffing head, tampico brush, cord brush, string buff, or brush-backed sander head. Abrasive-impregnated nylon disks mounted like buffs are also used, as are abrasive cloth sections mounted on a rotating hub. All of these methods produce about the same type of finish; the use of any particular one depends on the surface contour of the workpiece.

Surfaces of workpieces to be satin-finished should be free of grease and oil, and low contact pressures should be used. Wire brushes must be kept free of oxide and accumulations of aluminum metal. This is accomplished by frequently

bringing a pumice stone or soft brick in contact with the rotating brush. A common wire brushing setup consists of a 250 mm (10 in.) diameter wheel having a surface speed of about 8.0 m/s (1600 sfm) and wires 0.4 mm (0.015 in.) in diameter. Undue pressure on a rotating wire wheel will bend the wires and cause excessive tearing of the aluminum surface.

Stainless steel wires are recommended, because other metals such as brass or steel may become embedded in the aluminum surface, producing discoloration or corrosion. If brass or steel wire wheels are used, the embedded particles can be removed by immersing the work in a nitric acid solution (1 part water to 1 part acid by volume) at room temperature.

Table 8 Automatic bright-finish buffing of aluminum soleplates

Operation	Area buffed	Buffing head No.	Type	Size	Buffing wheel Diameter(a) Overall mm	in.	Arbor hole mm	in.	No. of sections	Speed m/s	sfm	Life, pieces	Application of compound(b) No. of guns	g per shot	oz per shot
1	Side	1, 2	Sisal	10 mm (⅜ in.) spiral sewed	410	16	40	1¼	2	37	7350	72,000	1	0.5	0.02
2	Side	3	Bias	16-ply, 20-spoke sewed	430	17	45	1¾	2	40	7800	72,000	1	0.5	0.02
3	Side	4	Bias	16-ply, 20-spoke sewed	430	17	45	1¾	2	40	7800	72,000	1	0.5	0.02
4	Top	5	Sisal	10 mm (⅜ in.) spiral sewed	410	16	45	1¾	15	37	7350	24,000	2	3.0	0.1
5	Top	6	Sisal	10 mm (⅜ in.) spiral sewed	410	16	45	1¾	15	37	7350	24,000	2	3.0	0.1
6	Top	7, 8	Bias	16-ply, 20-spoke sewed	430	17	45	1¾	10	40	7800	24,000	2	3.0	0.1

(a) All wheels had 180 mm (7 in.) diam centers. (b) Proprietary liquid compound was used. Cycle time: 0.12 s on, 13.0 s off

Table 9 Methods, equipment, and conditions for mechanical satin finishing of aluminum

Method	Suitable equipment Buffing lathe	Portable power head	Power required	Speed m/s	sfm	Lubricant
Wire brushing(a)	Yes	Yes	(b)	6-11	1200-2250	None
Sanding with brush-backed head(c)	Yes	No	(d)	900-1800 rev/min	900-1800 rev/min	Optional
Tampico or string brushing(e)	Yes	No	(b)	15-31	3000-6000	Pumice(f)
Finishing with abrasive-coated cloth(g)	Yes	Yes	(d)	31-36	6000-7000	Optional
Finishing with nylon disks(h)	Yes	Yes	(j)	23-33	4500-6500	Optional
Buffing with compounds(k)	Yes	Yes	(b)	15-26	3000-5000	(m)

(a) 305 mm (12 in.) diam brush of stainless steel wire 0.125 mm (0.005 in.) in diameter. (b) 1 hp per 25 mm (1 in.) of brush width. (c) Using 60- to 600-mesh abrasive cloth loadings. (d) 1 hp per head. (e) 300 mm. (12 in.) diam brush. (f) With oil or water; emery cake also may be used. (g) Cloth is mounted radially on rotating hubs; coated with 50- to 320-mesh emery abrasive. (h) Disks impregnated with silicon carbide abrasive, coarse to ultrafine. (j) ¼ hp per 25 mm (1 in.) of disk width. (k) Greaseless satin-finishing compounds containing aluminum oxide abrasive (200 or 240 mesh) used with unstitched or loosely stitched buffs (360 mm or 14 in.) or with string brush. (m) Dry, or with buffing compound or grease stick

The satin finish processes in which a greaseless abrasive compound is used are essentially dry. Water is required to soften the binder in the abrasive compound so that it will adhere to the surface of the buff. After the binder dries, the buff is ready for operation. At this stage a lubricant, such as a buffing compound or tallow, may be used to produce a higher reflection.

Table 9 describes the equipment and techniques employed in mechanical satin finishing processes. If the satin-finished parts are to be anodized, etching or bright dipping should not precede anodizing, because the satin appearance will be lost. Cleaning treatments that do not etch or that only slightly etch the metal should be used before anodizing.

Chemical Cleaning

The cleanliness requirements for an aluminum surface are governed by the subsequent finishing operations. For example, plating or the application of chromate or another mild-reaction conversion coating requires cleaning procedures that are somewhat more stringent than for anodizing.

When establishing a cleaning cycle or when testing different cleaners or cleaning conditions, it is desirable to test the cleanliness of the processed surface. Wetting an aluminum surface with water, known as the water break test, does not always provide an indication of cleanliness if oxides are of concern, because oxide-coated surfaces free of oil or grease can be wetted uniformly. Also, a surface that has been processed with a detergent containing a wetting agent can be wetted even though not thoroughly clean, because the film of wetting agent remains on the unclean surface. Two other methods of testing aluminum for cleanliness are to:

- Spray or coat the work surface with, or dip a test panel into, an unheated aqueous solution containing 30 g/L (4 oz/gal) of cupric chloride and 29 mL/L (3.8 fluid oz/gal) of concentrated hydrochloric acid. Uniform gassing or a deposit of copper indicates that the surface is chemically clean.
- Spray or coat the work surface with, or dip a test panel into, an unheated chromate conversion coating bath of the acid type until an orange-colored film is formed. A uniform orange film indicates a chemically clean surface.

Solvent Cleaning. The primary function of solvent cleaners is to remove oil and grease compounds. Organic solvents alone rarely provide sufficient cleaning to permit final finishing operations; solvents usually are used to remove large amounts of organic contaminants to minimize overloading of subsequently used alkaline cleaners.

Greases and oils vary as to solubility in specific solvents. Fish oils are more difficult to remove than other types of oils. In the dried condition, some oxidizing oils, such as linseed oil, form a leathery film that is difficult to remove with any solvent.

Polishing and buffing compounds are readily removed by most solvents when cleaning is performed immediately after buffing. If the compounds are permitted to harden, they may be difficult to remove. Heated solutions, agitation, or mechanical action (ultrasonics or physical force) may be required for satisfactory cleaning. To remove compounds burned in the surface, the parts must be soaked in a liquid using an organic degreaser, such as trichlorethylene or methylene dichloride (rather than vapor degreasing), or in an inhibited alkaline cleaner.

If polishing and buffing compounds cannot be removed immediately after buffing, the application of a neutral mineral oil over the buffed surface will maintain the compounds in a more soluble condition for subsequent removal by a solvent. The sequence of operations usually required for buffed aluminum surfaces is: solvent cleaning, rinsing, removal of surface oxides, rinsing, and finally the application of the desired finish. Some of these steps may be omitted, depending on the type and quality of the buffing compound, the quality of workmanship in buffing, and the quality of solvents and cleaners used.

Emulsifiable solvents also are used to clean aluminum. These are organic solvents, such as kerosene, Stoddard solvent, and mineral spirits, to which small amounts of emulsifiers and surfactants are added. In use, this type of cleaner emulsifies the oil or grease on the surface. The soil and cleaner are removed with water, preferably applied by spraying.

This type of degreasing is satisfactory prior to anodizing, etching, removal of surface oxides, chemical conversion coating, plating, or painting. In some instances, intermediate treatments are required, such as the removal of surface oxides before etching.

The emulsifiable solvent should have a pH of 8 or less; otherwise, it will stain or corrode the aluminum if permitted to remain on the surface prior to rinsing or additional cleaning. However, emulsifiable solvents with higher pH are more efficient cleaners, and they can be used if the surfaces are rinsed or are cleaned by additional methods within 2 or 3 min after degreasing.

A lower-cost cleaning solution can be obtained by adding water to the emulsifiable solvent. This less-efficient type of solution is limited to the removal of light oil and grease. It is now common practice to use alkaline cleaners to remove oil and grease instead of solvents, the use of which is under increasing scrutiny by the Environmental Protection Agency (EPA).

Alkaline cleaning is the most widely used method for cleaning aluminum and aluminum alloys. This method is easy to apply in production operations, and equipment costs are low. Aluminum is readily attacked by alkaline solutions. Most solutions are maintained at a pH between 9 and 11, and they are often inhibited to some degree to minimize or prevent attack on the metal. The most frequently used alkaline cleaner is the mildly inhibited type.

Cleaners of either the etching or nonetching type have some ability to emulsify vegetable and animal oils or greases, but not mineral oils or greases. Therefore, they can sometimes remove fresh buffing compounds and the lard oils used in spinning operations.

Nonetching cleaners can be classified as either silicated or nonsilicated. The silicated cleaners are based on aqueous solutions of sodium carbonate, trisodium phosphate, or other alkalis, to which small amounts of sodium silicate are added to inhibit etching. The main disadvantage of the silicated types, aside from their inability to emulsify and remove mineral oils, is that the silicate may react with the aluminum to form an insoluble aluminum silicate, especially when the temperature of the bath exceeds 80 °C (180 °F). However, lower operating temperatures decrease the efficiency of the solution for the removal of certain soils. Silicated alkaline cleaners are available that are used at 50 to 60 °C (120 to 140 °F) to reduce energy consumption.

Nonsilicated cleaners are often based on the use of relatively large concentrations of surfactants. High operating temperatures are required, but some cleaners used above 70 °C (160 °F) etch the aluminum surface. Cleaners containing a large quantity of surfactants, particularly those types that resist complete rinsing, must not be carried into baths used for bright dipping, anodizing, or chemical conversion coating.

Neither silicated nor nonsilicated cleaners remove aluminum oxide uniformly. Because oxide removal is essential for the application of decorative or functional finishes, the best procedure is to clean, remove oxide with an acid solution, and then proceed with finishing.

Nonetching cleaners may be used after solvent cleaning to produce water-wettable surfaces, or they may be used alone when soils are light and easily removed. The surfaces should be treated to remove oxides afterward. When sodium orthosilicate or sodium metasilicate is used, the concentration of carbonates must be kept at a minimum to minimize the formation of floc, which may redeposit on the work. Unlike sodium hydroxide, the alkali silicates have good wetting, emulsifying, and rinsing properties. The ratio of silicon dioxide to sodium oxide in the compound determines the effectiveness of the alkali sili-

cates. Sodium orthosilicate has good detergency and is effective in the cleaner at a ratio of 1 to 2, whereas the ratio of sodium metasilicate should be 1 to 1.

Agitation of the cleaner increases the cleaning action and is best created by pumps, propellers, or movement of the work. Air agitation, although easier to install and convenient to operate, has the following disadvantages:

- Air can reduce the solution temperature.
- The additional oxygen may cause staining and tarnishing on some alloys.
- Air agitation introduces carbon dioxide, which may increase the carbonate content.

The work should be rinsed immediately after removal from the alkaline bath to prevent dry-on. Warm water is preferred; if low-temperature cleaners are used, then rinsing with cold water is satisfactory.

Aluminum surfaces sometimes contain areas of localized corrosion, referred to as atmospheric etch, caused by contaminants in the air during storage. The corroded areas are more visible after alkaline cleaning or etching than before. When corrosion spots are present, the work may be dipped in a sodium bisulfate solution of 45 g/L (6 oz/gal), or in a cold 70% nitric acid solution, to minimize the effect of the subsequent alkaline cleaning.

During alkaline cleaning, especially if etching occurs, some alloys containing copper, iron, manganese, or silicon develop a black smut on the surface. Compositions and operating conditions of common alkaline cleaners are given in Table 10.

Electrocleaning is seldom used for cleaning aluminum and aluminum alloys, because it offers no advantage over an etching cleaner. However, a few processes are used in production operations. These use low voltage, usually in the range of 6 to 12 V. Cathodic cleaning, in which the work is the cathode, is more common than anodic cleaning. Common practice is to reverse the current during the last 5 to 10 s of the cleaning operation.

After removal from the cleaner, the work is rinsed in warm or hot water, dipped in acid to neutralize any residual alkali, and finally rinsed in cold water. The work can then be finished as desired. The composition of two solutions that are recommended for electrocleaning are:

Constituents	Composition, %
Solution A	
Sodium orthosilicate	85
Sodium carbonate (anhydrous)	10
Sodium resinate	5
Solution B	
Sodium carbonate (anhydrous)	46
Trisodium phosphate	32
Sodium hydroxide	16
Rosin	6

Note: For typical operating conditions, see text.

Table 10 Alkaline cleaners used to clean aluminum surfaces

Constituent or condition	Amount or value
Etching cleaners	
Sodium hydroxide	22-75 g (3-10 oz)
Sodium phosphate	0.8-4 g (0.1-0.5 oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-80 °C (140-180 °F)
Immersion time	30 s-10 min
Sodium hydroxide	2-6 g (0.25-0.75 oz)
Sodium phosphate	8-60 g (1-8 oz)
Sodium carbonate	8-60 g (1-8 oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-80 °C (140-180 °F)
Immersion time	2-5 min
Nonetching cleaners	
Sodium pyrophosphate and sodium metasilicate	Total of 15-75 g (2-10 oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-70 °C (140-160 °F)
Immersion time	2-5 min
Trisodium phosphate and sodium metasilicate	Total of 15-75 g (2-10 oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-70 °C (140-160 °F)
Immersion time	2-5 min
Sodium carbonate	4-8 g (0.5-1 oz)
Sodium metasilicate	4-8 g (0.5-1 oz)
Water, to make	4 L (1 gal)
Temperature of bath	6-70 °C (140-160 °F)
Immersion time	2-5 min
Borax	22-38 g (3-5 oz)
Sodium pyrophosphate	4-8 g (0.5-1 oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-70 °C (140-160 °F)
Immersion time	2-5 min

Acid Cleaning. Acid cleaners may be used alone or in conjunction with other acid, alkaline, or solvent cleaning systems. Vapor degreasing and alkaline cleaning may be required for the removal of heavy oils and grease from workpieces before they are immersed in an acid bath. One of the main functions of an acid cleaner is to remove surface oxides prior to resistance welding, painting, conversion coating, bright dipping, etching, or anodizing.

A mixture of chromic and sulfuric acids is commonly used to remove surface oxides, burnt-in oil, water stains, or other films, such as the iridescent or colored films formed during heat treating. This acid mixture cleans and imparts a slightly etched appearance to the surface, preparing it for painting, caustic etching, conversion coating, or anodizing. Nonpolluting, proprietary products free of chromic acid are available for acid cleaning and deoxidizing.

Oxide films must be thoroughly removed before spot welding. A mixture of phosphoric and chromic acids is another solution that can be used for this purpose. Because of the corrosive nature of the chlorides and fluorides in welding fluxes, the fluxes should be removed as soon as possible after welding. Mixtures of nitric and hydrofluoric acids are best for removing fluxes. Most fluxes can also be satisfactorily removed by a dilute (5 to 20 vol%) nitric acid solution.

Proprietary nonetching acid cleaners are available for cleaning aluminum and aluminum alloys. Operating temperatures of these solutions range

Table 11 Acid cleaners used to clean aluminum surfaces

Constituent or condition	Amount or value
Solution 1	
Chromic acid	45-90 g (6-12 oz)
Sulfuric acid (66° Bé)	150-190 mL (19-24 fluid oz)
Water, to make	4 L (1 gal)
Temperature of bath	45-80 °C (110-180 °F)
Immersion time	up to 20 min
Solution 2	
Nitric acid (42° Bé)	500-750 mL (64-96 fluid oz)
Hydrofluoric acid (48%)	25-190 mL (3-24 oz)
Water, to make	4 L (1 gal)
Temperature of bath	Room temperature
Immersion time	1-5 min
Solution 3	
Sulfuric acid (66° Bé)	100 mL (13 fluid oz)
Hydrofluoric acid (48%)	25 mL (3 fluid oz)
Chromic acid	40 g (5 oz)
Water, to make	4 L (1 gal)
Temperature of bath	65-70 °C (150-160 °F)
Immersion time	2-5 min
Solution 4	
Nitric acid (42 ° Bé)	38-125 mL (5-16 fluid oz)
Sodium sulfate (hydrate)	60-120 g (8-16 oz)
Water, to make	4 L (1 gal)
Temperature of bath	75-80 °C (170-175 °F)
Immersion time	4-8 min
Solution 5	
Phosphoric acid	70 mL (9 fluid oz)
Chromic acid	20 g (2.75 oz)
Water, to make	4 L (1 gal)
Temperature of bath	45-65 °C (110-150 °F)
Immersion time	1-5 min

from 55 to 80 °C (130 to 180 °F), and pH usually ranges from 4.0 to 5.7. Compositions and operating conditions for typical acid cleaning solutions are given in Table 11.

Aluminum parts should be insulated from ferrous metal baskets or supports when immersed in acid cleaning solutions, because contact of these two metals can produce a galvanic action that causes corrosion. Materials such as vinyl plastisols, epoxy, polyethylene, and polypropylene may be used for insulation. When practical, baskets or rods should be of the same or similar material as the workpieces.

Chemical Brightening (Polishing)

Chemical brightening, also known as bright dipping and chemical polishing, smoothens and brightens aluminum products by making use of the solution potential of the aluminum surface in the various baths employed and of the local differences in potential on the aluminum surface.

In general, chemical brightening baths can be concentrated or dilute acid solutions that contain oxidizing agents. The acids commonly used are sulfuric, nitric, phosphoric, acetic, and, to a lesser extent, chromic and hydrofluoric. Ammonium bifluoride is used when it is desirable to avoid the hazards that attend the use of hydrofluoric acid. Fluoboric and fluosilicic acids may also be used as alternates to hydrofluoric acid. An alkaline

bath, such as Alupol, can also be used for chemical etching. This bath consists of 20 kg (44 lb) sodium nitrate, 15 kg (33 lb) sodium nitrite, 25 kg (55 lb) sodium hydroxide, and 20 kg (44 lb) water. An aluminum part is immersed for 1 to 5 min at a bath temperature of 90 to 140 °C (195 to 285 °F). Protrusions, valleys, and scratches are eliminated, and reflectance is increased.

Phosphoric-Nitric Acid Baths. Among the various types of concentrated baths, the phosphoric-nitric acid baths are the most widely used in the United States. Compositions and operating conditions for two commercial baths of this type are given below:

Constituent or condition	Range
Phosphoric-nitric(a)	
Phosphoric acid (85%)	45-98 wt%(b)
Nitric acid (60%)	0.5-50 wt%(b)
Water	2 to 35 wt%
Temperature	85-110 °C (190-230 °F)
Immersion time	30 s to 5 min
Phosphoric-acetic-nitric(c)	
Phosphoric acid (85%)	80 vol%
Acetic acid (glacial, 99.5%)	15 vol%
Nitric acid (60%)	5 vol%
Temperature	85-110 °C (190-230 °F)
Immersion time	30 s to 5 min

(a) U.S. Patent 2,729,551 (1956). (b) Recommended volumetric make-up consists of 93.5 parts of 85% phosphoric acid and 6.5 parts of 60% nitric acid. (c) U.S. Patent 2,650,157 (1953)

Additionally, certain proprietary chemical bright dips can be operated at 75 to 80 °C (170 to 180 °F), which is significantly lower than the normal 85 to 110 °C (190 to 230 °F) for conventional baths. The low-temperature baths, however, are limited in allowable water drag-in from prior rinse operations. Excessive water drag-in results in poor brightening.

Alkali nitrates may be used as substitutes for nitric acid. Acetic acid, copper salts, and other additives are used in some phosphoric-nitric acid baths. As additive content increases, solution control becomes more complex.

For economy, some phosphoric-nitric acid baths are operated with an aluminum phosphate content near the tolerable maximum of 10 to 12%, with a dissolved aluminum content of about 40 g/L (5 oz/gal). This is close to the saturation point, at which precipitation of this compound on the work produces etch patterns.

The addition of surfactants increases the amount of metal removed under a given set of operating conditions. Surfactants help to enhance the chemical polishing as well as to suppress the evolution of fumes. Acetic and sulfuric acids alter the physical property/composition relationship in the concentrated acid baths and also complicate control problems. Acetic acid volatilizes rapidly from the bath.

Small concentrations of heavy metals in the bath enhance the brightening effect, particularly on alloys with negligible copper content. Copper can be introduced into the bath by one of three methods: the direct dissolution of a small amount

of copper; the addition of a small amount of a copper compound, such as 0.01 to 0.02% cupric nitrate; or the use of racks made of aluminum-copper alloys. Copper is added to the bath when brightening aluminum alloys such as 2024 and 7075, which contain high percentages of copper. Excess copper can plate out of the bath. In some baths, however, excess copper causes etching, and sometimes nickel or zinc is used instead.

Phosphoric-nitric acid baths are not recommended for brightening alloys that contain silicon. Excessive dissolution causes dispersion of undissolved silicon, which deposits on the work surfaces and is difficult to remove by rinsing. When high-silicon alloys are used, the addition of 1 to 2% hydrofluoric acid to the bath is recommended. The gradual buildup of other metals in the bath from the aluminum alloys processed usually causes no difficulty unless the amount of aluminum dissolved exceeds the solubility limit. When this occurs, excess aluminum precipitates and causes coprecipitation of trace elements, which may be difficult to remove from the work.

Contamination of the bath by more than trace amounts of buffing or polishing compounds and other soils should be avoided. These compounds may cause the bath to foam excessively and may interfere with its polishing action. Food-grade or National Formulary phosphoric acid should be used. Lower grades contain fluorides, arsenic, and other impurities that are harmful to the process.

Close control of the nitric acid and water contents, necessary for optimum chemical brightening, is difficult because of the rapid volatilization of these liquids and because of the time required for chemical analysis of the bath. A control method based on an electronic device that monitors the nitric acid content and on the physical measurement of specific gravity and viscosity has been developed.

Drag-out is a major factor in the cost of chemical brightening. The amount of solution and the weight of chemicals lost by drag-out are related to the specific gravity and viscosity of the solution. Drag-out can be minimized by operating the bath at higher temperatures, but this condition may increase the amount of transfer etch while moving to the rinse tank, as well as the rate of aluminum dissolution and the rate of evaporation of nitric acid and water. However, transfer etch can be avoided by rapid transfer into the rinse, and the rate of aluminum dissolution can be minimized by a shorter period of immersion. In general, an operating temperature in the range of 85 to 100 °C (190 to 212 °F) is satisfactory, provided an optimum bath composition, including additives, is maintained. Also, evaporation of nitric acid and water is not excessive at this temperature. Acetic acid also reduces transfer etch, but this acid volatilizes rapidly from the bath.

Surfactants are employed in some baths to suppress the evolution of fumes; however, they may cause foaming and increase the amount of drag-out. Surfactants also increase the rate of workpiece dissolution. The generation of heat accompanying high dissolution rates must be

Table 12 Electrolytic brightening and polishing solutions and processes for use on aluminum and aluminum alloys

Bath	Percentage	Temperature		Dura-tion, min	Volt-age, V	Current density		Film thickness		Appearance properties	Remarks
		°C	°F			A/dm²	A/ft²	μm	mils		
Seignette salt brightener (alkaline process)											
Sodium potassium tartrate	15 wt%	38-42	100-108	2-15	10	3-5	30-50	...	...	High luster, mirror-like reflectivity	For pure aluminum, Raffinal, Reflektal, and for jewelry and reflectors
Sodium hydroxide	1.2 wt%										
Aluminum powder	0.2 wt%										
Water	83.6 wt%										
Acid brightening											
Sulfuric acid	70 vol%	75-85	167-185	2-10	10-20	10-15	100-150	...	...	High luster, mirror-like reflectivity	For pure aluminum, and its alloys and for reflectors, architectural and structural shapes, and appliance parts
Phosphoric acid	15 vol%										
Nitric acid	1 vol%										
Water	14 vol%										
VAW brightener											
Sodium bisulfate	20 wt%	87-93	188-199	8-10	8-10	10-15	100-150	...	...	Colorless, transparent oxide film with effect on reflectivity	Used as a post-treatment after conventional anodizing is accomplished
Sodium sulfate	10 wt%										
Sodium hydroxide	1 wt%										
Water	69 wt%										
Smudge remover											
Sodium carbonate	2 wt%	92-97	198-207	...	...	...	...	...	...	Preserve reflectivity	For removing the thin film produced on the aluminum surface by electrobrightening, which otherwise would impair reflectivity
Sodium dichromate	1.5 wt%										
Water	96.5 wt%										
Anodic post-treatments											
Sulfuric acid	71 wt%	23-27	74-81	10	12	1	10	4	0.1	Colorless, transparent film	Without anodizing good results; best results with anodizing
Water	93 wt%										
Sulfuric acid	10-20 wt%	18-22	64-72	10	12	1	10	4	0.1	Colorless, transparent film	Without anodizing good results; best results with anodizing
Water	90-80 wt%										
Sodium bisulfate	20 wt%	33-37	91-98	10	10	0.5	5	2	0.08	Colorless, transparent film	Without anodizing good results; best results with anodizing
Water	80 wt%										

considered when providing for the control of bath temperatures within the specified range.

Agitation is useful for maintaining a uniform temperature and composition throughout the bath, and for fast removal of reaction products and replenishment of reactants at the surfaces of the work. The most satisfactory method is mechanical agitation and movement of the work in an elliptical pattern. Air agitation is commonly used, but it must be properly controlled. Small air bubbles cause excessive loss of volatile acids by evaporation and an excess of nitrous oxide fumes. Large air bubbles sufficient to create uniform bath temperature provide satisfactory agitation. Excessive solution agitation can cause pitting and streaking on work, so the agitation should always be moderate.

The bath must be well vented to remove the noxious fumes; an exhaust of about 90 m³/min per square meter (300 ft³/min per square foot) of bath surface is recommended. Fumes evolved during transfer of the parts to the first rinse tank should likewise be vented, and it is good practice also to vent the first rinse tank, for which an exhaust of about 60 m³/min per square meter (200 ft³/min per square foot) of water surface is satisfactory. Water should be warm and air-agitated.

The fumes can be exhausted by fan or steam jet. Fume separators are required when the fumes cannot be exhausted into the atmosphere. Dilute caustic soda solutions are used to scrub the fumes and neutralize the acid.

Phosphoric and Phosphoric-Sulfuric Acid Baths. Concentrated solutions of phosphoric acid at operating temperatures above 80 °C (175 °F)

were the first baths used for brightening aluminum. A more effective bath, which combines some smoothening or polishing with brightening action, is one containing 75 vol% phosphoric acid and 25 vol% sulfuric acid. This bath, which is operated at 90 to 110 °C (195 to 230 °F) for 30 s to 2 min, produces a diffuse but bright finish.

Under some conditions of composition and bath temperature, a white film of phosphate salts remains on the metal after treatment in either of these baths. The film must be removed by using a hot (60 to 70 °C, or 140 to 160 °F) aqueous solution of chromic and sulfuric acids. The composition of this acid solution is not critical and may range from 2 to 4% CrO_3 and 10 to 15% H_2SO_4 by weight.

Electrolytic Brightening (Electropolishing)

Electrolytic brightening, also known as electrobrightening and electropolishing, produces smooth and bright surfaces similar to those that result from chemical brightening. After pretreatment (which consists of buffing, cleaning in an inhibited alkaline soak cleaner, and thorough rinsing) the work is immersed in the electrobrightening bath, through which direct current is passed. The work is the anode.

Solution compositions and operating conditions for three commercial electrolytic brightening processes, as well as for suitable post-treatments, are given in Table 12. Operating conditions for electrolytes used in electrobrightening are selected to produce the desired selective

dissolution and may vary for optimum results on different aluminum alloys.

Fluoboric acid electrobrightening operating conditions and suitable post-treatments are given in Table 13. This process can be used for specular and diffuse reflectors, products made of super-purity aluminum (99.99%) in combination with up to 2% Mg, and products made of high-purity aluminum (99.7 to 99.9%).

Sodium carbonate electrobrightening can be used for specular reflectors, automotive trim, decorative ware, and jewelry. It can also be used for products made of super-purity aluminum in combination with up to 2% Mg, products made of high-purity aluminum, and products made of the following commercial alloys (in approximate order of decreasing quality of finish): 5457, 5357, 6463, 6063, 5052, 1100, 5005, 3003, and 6061. Sodium carbonate electrobrightening operating conditions and suitable post-treatments are given in Table 14.

Sulfuric-phosphoric-chromic acid electrobrightening operating conditions and suitable post-treatments are given in Table 15. This process is used primarily for macrosmoothening to replace mechanical polishing wholly or in part. Other applications include architectural trim, decorative ware, jewelry, and products made of commercial alloys.

Selection of Chemical and Electrolytic Brightening Processes

Chemical and electrolytic brightening are essentially selective-dissolution processes, in

Table 13 Fluoboric acid electrobrightening of aluminum and aluminum alloys

Constituent or condition	Amount or value
Electrobrightening(a)	
Fluoboric acid	2.5 wt%
Temperature of bath	30 °C (85 °F)
Current density	1-2 A/dm^2 (10-20 A/ft^2)
Voltage	15-30 V
Immersion time	5-10 min
Agitation	None
Smut removal	
Phosphoric acid	1.0 wt%
Chromic acid	0.5 wt%
Temperature of bath	90-95 °C (190-200 °F)
Immersion time	30 s
Anodizing	
Sulfuric acid	7-15 wt%
Current density	1.3 A/dm^2 (12 A/ft^2)
Temperature of bath	20 °C (70 °F)
Immersion time	10 min
Sealing	
Distilled water	100%
Temperature of bath	95-100 °C (200-212 °F)
Immersion time	10 min

(a) U.S. Patent 2,108,603 (1938)

Table 14 Sodium carbonate electrobrightening of aluminum and aluminum alloys

Constituent or condition	Amount or value
Electrobrightening	
Sodium carbonate (anhydrous)	15 wt%
Trisodium phosphate	5 wt%
pH	10.5
Temperature of bath	80-82 °C (175-180 °F)
Current density	2-3 A/dm^2 (20-30 A/ft^2)
Voltage	9-12 V
Initial immersion without current	20 s
Immersion time with current	5 min
Agitation	Work rod only
Anodizing(b)	
Sodium bisulfate	20 wt%
Temperature of bath	35 °C (95 °F)
Current density	0.5 A/dm^2 (5 A/ft^2)
Voltage	10 V
Immersion time	15 min
Smut removal(a)	
Sulfuric acid	10 vol%
Temperature of bath	20-25 °C (70-80 °F)
Immersion time	15-30 s
Sealing	
Distilled water	100%
Temperature of bath	85 °C (185 °F)
Immersion time	20 min

(a) Smut may also be removed mechanically. (b) The anodizing treatment in the preceding list may be used as an alternative.

Table 15 Sulfuric-phosphoric-chromic acid electrobrightening of aluminum and aluminum alloys

Constituent or condition	Amount or value
Electrobrightening(a)	
Sulfuric acid	4-45 wt%
Phosphoric acid	40-80 wt%
Chromic acid	0.2-9.0 wt%
Trivalent metals	6 wt% max
Temperature of bath	70-95 °C (160-200 °F)
Viscosity of bath at 82 °C (180 °F)	9-13 cP
Current density	2.5-95 A/dm^2 (25-950 A/ft^2)
Voltage	7-15 V
Agitation	Mechanical
Smut removal	
Phosphoric acid	3.5 wt%
Chromic acid	2.0 wt%
Temperature of bath	90-95 °C (190-200 °F)
Anodizing	
Sulfuric acid	7-15 wt%
Current density	1.2 A/dm^2 (12 A/ft^2)
Temperature of bath	20 °C (70 °F)
Immersion time	10-20 min
Sealing	
Distilled water	100%
Temperature of bath	95-100 °C (200-212 °F)
Immersion time	10 min

(a) U.S. Patent 2,550,544 (1951)

which the high points of a rough surface are attacked more rapidly than the depressions. An important feature of these processes is their ability to remove a surface skin of metal that is contaminated with oxides and with traces of residual polishing and buffing compounds, or other inclusions, while at the same time brightening the surface.

Metallurgical Factors. The composition, orientation, and size of the individual grains within a workpiece have a direct effect on the uniformity of dissolution during brightening. Fine-grain material is the most desirable for chemical or electrolytic brightening. Best results are obtained with alloys that are of uniform chemical composition and that do not precipitate constituents of different potential from the matrix during any necessary heating or heat treatment. Also, the alloys should be such that forming operations cause only relatively minor detrimental effects.

Mill operations must be controlled to produce material that can be brightened satisfactorily. It is important that the material be fine-grain and that surfaces be free of imperfections, such as segregation, oxide inclusions, laps, die marks, and stains.

Optical Factors. In general, the highest total and specular reflectance of a brightened surface is obtained on pure aluminum having a fine grain structure. Reflectance, both total and specular, decreases as alloy content increases; however, at a given alloy content the decrease will vary with the process. Magnesium has a very small effect on reflectance. The effect of alloying elements varies greatly with different brightening processes.

In a few applications, chemically or electrolytically brightened surfaces are protected by a clear organic coating. However, most surfaces bright-ened by these methods are anodized to produce a clear, colorless, protective oxide coating. For many decorative uses, the anodic coating is subsequently dyed.

Applications of chemical and electrolytic brightening processes are functional and decorative. They include jewelry, razor parts, automotive trim, fountain pens, searchlight reflectors, natural-finish or brightly colored giftware, architectural trim, household appliances, and thermal reflectors for components of space vehicles.

Chemical and electrolytic brightening may be used before or after buffing, as an intermediate operation, or to replace buffing either completely or partly. In processes where brightening is used to replace buffing completely, aluminum is dissolved at relatively rapid rates, and 25 μm (1 mil) or more of metal is removed. In processes where brightening is used as the final operation of the finishing sequence, metal is dissolved more slowly, and total metal removal usually ranges from about 3 to 13 μm (0.1 to 0.5 mil). Such procedures are used primarily on super-purity aluminum with up to 2% Mg and on high-purity aluminum.

Chemical versus Electrolytic Brightening. Because of improvements in chemical brightening processes, brightening results are equivalent to those obtained by the electrolytic processes, with the exception of reflector-type finishes on super-purity and high-purity aluminum.

Initial and operating costs for equipment are lower for chemical brightening than for electrolytic brightening, because electrical power and associated equipment are not required. Chemical brightening can be used on a variety of alloys.

Electrobrightening processes can have low chemical costs, because the chemicals used are less expensive and because baths operate well at high levels of dissolved aluminum. Other advantages of some baths used in electrobrightening are chemical stability of the solution and the ability of the bath to operate continuously for long periods at optimum efficiency with relatively simple control.

Advantages over Buffing. In performance and economy, chemical and electrolytic polishing processes offer the following advantages over buffing:

Performance

- Contaminants are not introduced into the metal surface. Chemical or electrolytic processes remove trace amounts of contaminants initially present in the surface skin or embedded in the metal during prior operations. Surfaces brightened by these processes have better total and specular reflectance.
- Anodized and dyed surfaces that have been chemically or electrolytically brightened have a brilliance, clarity, and depth not attainable with buffed surfaces. Anodizing reduces the reflectance values of chemically or electrolytically brightened surfaces less than it reduces the reflectance of buffed surfaces.
- Chemical or electrolytic brightening of aluminum prior to electroplating provides better adhesion and continuity of the plated deposits.

This improves corrosion resistance and serviceability.

Economy

- Labor costs are lower than for buffing.
- Processes are readily adaptable to high-production parts that, because of their shape, cannot be finished on automatic buffing machines, and to parts that require buffing of a large percentage of the total surface area. Modification of automatic buffing machines to accommodate parts of different shapes may be more expensive than changes in racking for chemical or electrolytic brightening of these parts.
- Incorporation of processes into an automatic anodizing or electroplating line can result in economies in terms of space, equipment, and operations, and it may eliminate one or more cleaning or pickling operations in the pretreatment cycle. Deburring can sometimes be completely eliminated because of the high rate of metal removal on edges and corners.

Chemical Etching

Chemical etching, using either alkaline or acid solutions, produces a matte finish on aluminum products. The process may be used for final finishing, but it is more often used as an intermediate step prior to lacquering, conversion coating, anodizing, or other finishing treatments. Chemical etching also is used extensively in conjunction with buffing or chemical brightening.

The advantages of etching with alkaline or acid solution prior to anodizing are that it removes oxide films and embedded surface contaminants that otherwise would discolor the anodic coating; roughens the surface slightly, to produce a less glossy anodized surface and to minimize slight differences in the mill finish of different production lots; and minimizes color-matching differences, which are more apparent with glossy or specular surfaces. Matte finishes are readily produced by chemical etching on the following wrought and cast aluminum alloys:

Wrought alloys

- *Sheet and plate:* 1100, 2014, 2024, 3003, 5005, 5052, 5457, 6061, 7075
- *Extrusions:* 2014, 2024, 6061, 6063, 6463, 7075

Casting alloys

- 242, 295, 514, A514, B514, F514, 518, 510

Cleaning prior to etching is recommended for attainment of the highest-quality finish. The need for prior cleaning, however, is determined by the amount and type of soil present on the surface of work being processed. In many instances, the etching solution serves as both a cleaner and a finishing medium.

Post-Treatments. Subsequent treatments, such as anodizing or chromate conversion coating,

are required for protection against corrosion and against mechanical damage to the soft, easily marred surface. Clear lacquer may be applied to protect the matte finish produced by the etching process. Before being lacquered, the work must be cleaned of etching smut, thoroughly rinsed in clean cold water, and dried in warm air. Lacquering or painting should be done as soon as possible in a clean atmosphere.

Alkaline Etching

Alkaline etching reduces or eliminates surface scratches, nicks, extrusion die lines, and other imperfections. However, some surface contaminants, if not removed before the work enters the etching solution, may accentuate these imperfections during etching. Oxides, rolled-in dirt, and many other surface contaminants can sometimes be eliminated by deoxidizing the work with a 2 to 4 wt% chromic acid/10 to 15 wt% sulfuric acid etchant at 60 to 70 °C (140 to 160 °F) prior to alkaline etching. This treatment removes stains resulting from heat treatment and other causes without removing much metal.

Solution Makeup and Control. A hot (50 to 80 °C, or 120 to 180 °F) solution of sodium hydroxide, potassium hydroxide, trisodium phosphate, or sodium carbonate is used for alkaline etching. The solution may contain more than one alkali. The use of uninhibited alkaline solutions (such as sodium hydroxide solutions) is not recommended for high-strength 7xxx and 2xxx aluminum alloys in certain artificially aged tempers because of the danger of intergranular attack.

Sequestrants, such as gluconic acid, sodium gluconate, the glucamines, and sorbitol, are added to alkaline solutions to prevent the formation of hydrated alumina. If permitted to form, this compound coats tank walls and heating coils with a difficult-to-remove scale. Sequestrants increase the life of the bath by preventing the formation of scale and by reducing the accumulation of sludge in the tank. They are added in concentrations of 1 to 5%.

Sodium hydroxide is the alkali most commonly used. Its reaction with aluminum is exothermic, produces hydrogen gas and sodium aluminate, and may increase the temperature of the bath, depending on the relationship between rate of metal removal and tank volume. Uniform finishes may thus be more difficult to obtain with large loads or rapid dissolution rates in small tanks, because the increase in temperature causes faster etching and more rapid depletion of the chemical constituents in the bath.

The concentration of sodium hydroxide in the etching solution usually ranges from 15 to 60 g/L (2 to 8 oz/gal). For most applications, a concentration of 30 to 45 g/L (4 to 6 oz/gal) is adequate. The choice of concentration is influenced by the finish desired, the operating temperature of the bath, the quality of water, the transfer time between the etchant and rinse, and the amount of drag-out.

Solution control is guided by regular titration of samples to determine free sodium hydroxide and sodium aluminate (aluminum). In a common method of operation, the concentration of free sodium hydroxide is not permitted to fall below 26 or 30 g/L (3.5 or 4 oz/gal) when a uniform, medium-deep etch is required. The normal working concentration of aluminum is about 30 g/L (4 oz/gal), or about 2.5 wt%. When the aluminum content of the solution approaches 55 to 75 g/L (7 to 10 oz/gal) and the free sodium hydroxide content about 40 g/L (5 oz/gal), the finish may become brighter and more reflective, indicating that the solution is nearly exhausted and should be partly or completely replaced.

Determination of specific gravity also is useful in solution control. A solution that has a specific gravity of 1.15 to 1.18 while maintaining a free sodium hydroxide content of 30 to 38 g/L (4 to 5 oz/gal) is considered to be approaching exhaustion. When this condition is reached, the finish being produced should be carefully observed for nonuniform etching and shiny appearance. As the aluminum content of the solution increases, the solution becomes more viscous, which may result in poor rinsing and greater drag-out. Special proprietary rinse additives are available that help to reduce the drag-out and streaking problems caused by high viscosity of the etchant.

Environmental regulations have led to the development of waste recovery technology for used caustic etching solutions. These baths can be operated without any chelating agents, such as sodium gluconate. Recovery processes depend on a controlled precipitation of dissolved aluminum with an accompanying regeneration of free sodium hydroxide. Closed-loop recovery systems of this type also reduce chemical costs and provide more uniform etching. Because of the high capital investment required, these recovery processes are most feasible for large installations.

Equipment and Operating Procedures. Tanks and heating coils for alkaline etching may be made of low-carbon steel. Ventilation is required for the etching tanks, because the mistlike fumes generated are a health hazard to personnel, and because alkali-contaminated air can corrode or etch unprotected aluminum in the work area, especially during periods of high humidity. Efficient venting should be provided to exhaust the fumes and spray generated during the transfer of the parts to the first rinse tank.

Sometimes a blanket of foam on the solution is used to reduce the amount of mist. Foam is usually created by the addition of surface-active, or wetting, agents to the bath. A layer of 25 or 50 mm (1 or 2 in.) of foam on the surface of the bath is usually adequate.

Work to be processed may be placed on appropriate racks or loaded in baskets for immersion in the etching solution. Dipping is the method most often used for etching, although in some instances spray etching has been used. Workpieces to be bulk-processed in baskets must be positioned to prevent the formation of air or gas pockets. For best results, it is desirable to agitate the solution by air or by movement of the work.

Racks and baskets are usually used when etching is followed by subsequent treatments, such as chemical brightening or conversion coating. Stainless steel is a suitable material for bulk-etching baskets, because it withstands the corrosive conditions of the various solutions used in the cleaning and finishing processes. Baskets for bulk etching cannot be used for anodizing because an electrical contact cannot be made. Bulk parts must be transferred to specially designed containers with a pressure contact prior to anodizing.

In general, bath temperatures range from 50 to 80 °C (120 to 180 °F). Specific operating temperature is determined by the final finish desired, the time cycle, available equipment, and the concentration of the bath constituents.

After etching, the work should be rinsed immediately. A high etching temperature and a long transfer time from the etching tank may cause dry-on of the etchant. This condition produces a nonuniform finish characterized by cloudy, pitted, or stained areas.

An air-agitated rinse is beneficial, as is a double rinse in cold water flowing in a countercurrent. The latter method uses smaller tanks, uses less water, and produces better rinsing than the use of warm water or only one rinse tank. Warm water may cause staining as a result of postetching, especially when only one rinse tank is used. The work should not remain too long in the first rinse tank following etching, because the tank usually contains sufficient residual sodium hydroxide to cause staining or a cloudy finish.

Spot welds, riveted areas, and folded edges may contain small cracks or crevices that entrap the alkaline solution. Rinsing may not remove the entrapped solution; the alkaline solution will subsequently bleed out and leave a residue of white powder after the finishing process is completed. Bleed-out also can occur after anodizing. Bleed-out is unattractive and can cause failure of organic films, such as lacquers and paints, applied for added protection.

Dimensional Changes. Etching in alkaline solutions can remove a considerable amount of metal. Figure 1 shows the dimensional changes that occurred when sheet materials of various aluminum-base alloys were etched for 1, 2, or 3 min in air-agitated sodium hydroxide solution (5 wt% NaOH) operated at 70 ± 5 °C (160 ± 5 °F). When clad materials are being treated, the etching cycle must be carefully controlled to prevent loss of the cladding.

Desmutting. During the cleaning and etching operation, smut (a gray-to-black residual film) is deposited on the surface of the work. This deposit usually consists of iron, silicon, copper, or other alloying constituents (in an aluminum-base material) that are insoluble in sodium hydroxide. When etching is to be followed by anodizing, the smut can sometimes be removed by the anodizing solution (current flowing); however, this practice generally cannot be controlled to produce a finish of uniform appearance. Copper and iron smuts dissolved in the anodizing electrolyte can accumulate until they make necessary premature disposal of the electro-

lyte. The recommended procedure is to remove the smut in a solution prepared specifically for this purpose.

A nitric acid solution (10 to 15 vol% HNO₃ or more) will remove smut. A solution containing 0.5 to 1 wt% chromic acid plus 4 to 6 wt% sodium bisulfate is similarly effective. Solutions of proprietary compounds that are nonchromated and hence nonpolluting are also used. Fluorides are usually added to solutions to aid the removal of smut from high-silicon aluminum alloys and aluminum die castings. Good results have been obtained with a room-temperature solution of 3 parts nitric acid and 1 part hydrofluoric acid.

The following example describes the solution to a problem encountered in the desmutting of die castings of a high-silicon alloy that was etched in a sodium hydroxide solution.

Because of the high silicon content of alloy 380.0 (7.5 to 9.5% Si), desmutting to obtain an attractive, uniform finish on the die castings was difficult. A chromate-type desmutting solution had been used after etching in sodium hydroxide, but it had not been entirely effective. The addition of an acid fluoride etch provided the desired finish. The sequence of operations used was as follows:

1. Soak in nonetching aluminum cleaner at 60 to 65 °C (140 to 150 °F) for 5 to 10 min.
2. Rinse in cold water.
3. Etch for 60 to 90 s in a sodium hydroxide etching solution at 60 to 65 °C (140 to 150 °F).
4. Rinse in cold water.
5. Remove part of the smut by immersing in an air-agitated, chromate-type desmutting solution at room temperature.
6. Rinse in cold water.
7. Immerse in a room-temperature acid etching solution containing fluoride and nitric acid for 30 to 60 s to remove the remaining smut.
8. Rinse in cold water.

After being prepared in this manner, the castings were chromate-conversion coated and dipped in lacquer.

Proprietary chromic-sulfuric acid desmutting solutions generally require a tank made of type 302 or 304 stainless steel, although some solutions may require type 316 or 347. They are usually operated at room temperature and normally do not require ventilation. This is an advantage over nitric acid solutions. A disadvantage of some proprietary solutions is the need for treatment of the wastes to remove the harmful effects of chromium salts before the wastes are discharged from the plant. EPA regulations and local ordinances regulate the disposition of waste solutions.

Hexavalent chromium compounds and nitric acid are especially undesirable from an EPA environmental viewpoint. As a result, these traditionally effective oxidizing agents are frequently replaced with such compounds as ferric salts, persulfates, and peroxides. (Additional information is available in the article "Chromium Elimination" in this Volume.)

Acid Etching

Acid solutions are commonly used for finished castings, especially those made of high-silicon alloys. Acid etching can be done without heavy smut problems, particularly on aluminum die castings. Hydrochloric, hydrofluoric, nitric, phosphoric, chromic, and sulfuric acids are used in acid etching.

Combinations of these acids and mixtures of acids and salts are often used for specific applications. Sulfuric-chromic acid solutions remove heat-treating stains with little etching of the metal; dilute hydrofluoric-nitric acid solutions produce bright, slightly matte-textured surfaces; and hydrochloric acid containing sodium chloride and ferric chloride is used for deep etching of designs. Additions of cobalt and nickel salts to the hydrochloric acid solution accelerate etching, but they do not affect the ability of the solution to produce a sufficiently smooth surface. Alloys containing silicon, such as sand castings, should be acid-etched with a 2 to 5% aqueous solution of hydrofluoric acid prior to anodizing.
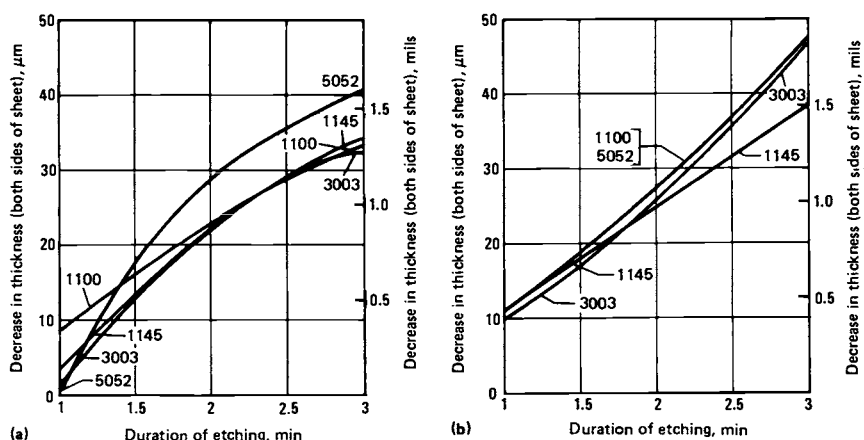

Fig. 1 Effect of time on the amount of metal removed from aluminum alloys during alkaline etching. (a) By micrometer measurement. (b) Calculated from loss in weight. Both solutions contain 5 wt% NaOH at 70 ± 5 °C (160 ± 5 °F).

Compositions and operating conditions for three acid etching solutions are:

Solution 1

Nitric acid	3 parts by vol
Hydrofluoric acid	1 part by vol
Temperature of bath	20 °C (70 °F) max
Immersion time	15 s to 1 min

Solution 2

Chromic acid	80 g (10.5 oz)
Sulfuric acid	675 mL (22.4 fluid oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-70 °C (140-160 °F)
Immersion time	30 s to 2 min

Solution 3

Chromic acid	175 g (23.5 oz)
Sulfuric acid	75 mL (2.5 fluid oz)
Water, to make	4 L (1 gal)
Temperature of bath	60-70 °C (140-160 °F)
Immersion time	30 s to 2 min

Figure 2 is a flow chart of the operations used in acid etching.

Fumes from most acid etching solutions are corrosive, and the mist or spray carried up by the gases generated constitutes a health hazard. Ventilation is required, even for solutions operated at room temperature. Tanks are made of stainless steel or plastic, or are plastic lined; plastic or plastic-lined tanks are used with solutions containing hydrochloric or hydrofluoric acid. Cooling coils may be required, because etching generates heat. Heating coils are required for solutions operated at elevated temperatures.

Acid etching is often used alone, but sometimes it may either precede or follow alkaline etching. It is usually used before alkaline etching when oxides are to be removed and after alkaline etching when smut removal is a problem. Acid etching solutions, especially those containing fluorides, are excellent smut and scale removers. After acid etching and thorough rinsing, the work is ready for further processing (Fig. 2).

Anodizing

The basic reaction in all anodizing processes is the conversion of the aluminum surface to aluminum oxide while the part is the anode in an electrolytic cell. Aluminum surfaces are anodized for a number of reasons, including to:

- Increase corrosion resistance
- Increase paint adhesion
- Prepare the surface for subsequent plating
- Improve adhesive bonding
- Improve decorative appearance
- Provide electrical insulation
- Permit application of photographic and lithographic emulsions
- Increase emissivity
- Increase abrasion resistance
- Permit detection of surface flaws

The three principal types of anodizing processes are:

- *Chromic anodizing,* in which the agent is chromic acid
- *Sulfuric anodizing,* in which the active agent is sulfuric acid
- *Hard anodizing,* in which the agent is sulfuric acid, alone or in combination with additives

Other processes, used less frequently or for special purposes, employ sulfuric-oxalic, phosphoric, oxalic, boric, sulfosalicylic, or sulfophthalic acid solutions. Except for those produced by hard anodizing processes, most anodic coatings range in thickness from 5 to 18 μm (0.2 to 0.7 mil). The succession of operations typically employed in anodizing is illustrated in Fig. 3.

The three major anodizing processes, as well as anodizing equipment, applications, troubleshooting, and coating evaluation, are described in detail in the article "Anodizing" in this Volume.

Chemical Conversion Coating

Chemical conversion coatings are adherent surface layers of low-solubility oxide, phosphate, or chromate compounds produced by the reaction of suitable reagents with the metallic surface. These coatings affect the appearance, electrochemical potential, electrical resistivity, surface hardness, absorption, and other surface properties of the material. They differ from anodic coatings in that conversion coatings are formed by a chemical oxidation-reduction reaction at the surface of the aluminum, whereas anodic coatings are formed by an electrochemical reaction. The reaction that takes place in chemical conversion coating involves the removal of 0.3 to 2.5 μm (0.01 to 0.1 mil) of the material being treated.

Conversion coatings are excellent for:

- Corrosion retardation under supplementary organic finishes or films of oil or wax
- Improved adhesion for organic finishes
- Mild wear resistance
- Enhanced drawing or forming characteristics
- Corrosion retardation without materially changing electrical resistivity
- Decorative purposes, when colored or dyed

Conversion coatings are used interchangeably with anodic coatings in organic finishing schedules. One use of conversion coating is as a spot treatment for the repair of damaged areas in anodic coatings. Because of their low strength, conversion coatings should not be used on surfaces to which adhesives will be applied. Anodic coatings are stronger than conversion coatings for adhesive bonding applications.

The simplicity of the basic process, together with the fact that solutions may be applied by immersion, spraying, brushing, wiping, or any other wetting method, makes conversion coating convenient for production operations. Some applications using chemical conversion coatings on various aluminum alloys are given in Table 16. In most installations, conversion coating offers a cost advantage over electrolytic methods. Moreover, unlike some anodic coatings, chemical conversion coatings do not lower the fatigue resistance of the metal treated.

Procedure. The sequence of operations for applying a satisfactory conversion coating to aluminum-base materials is as follows:

- Removal of organic contaminants
- Removal of oxide or corrosion products
- Conditioning of the clean surface to make it susceptible to coating
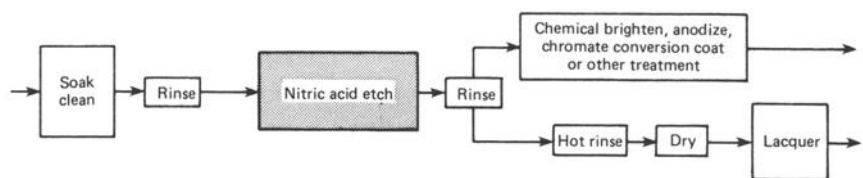- Conversion coating

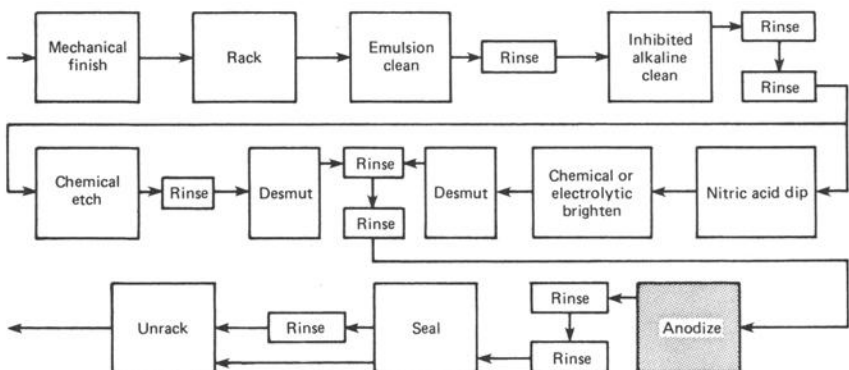**Fig. 2** Operations used in etching of aluminum and aluminum alloys

Fig. 3 Typical sequence of operations for anodizing aluminum alloys

Table 16 Applications of aluminum using chemical conversion coatings

Application	Aluminum alloy	Subsequent coating
Oxide conversion coatings		
Baking pans(a)	1100, 3003, 3004, 5005, 5052	Silicone resin
Phosphate conversion coatings		
Screen cloth	5056	Clear varnish
Storm doors	6063	Acrylic paint(b)
Cans	3004	Sanitary lacquer
Fencing	6061	None applied
Chromate conversion coatings		
Aircraft fuselage skins	7075 clad with 7072	Zinc chromate primer
Electronic chassis	6061-T4	None applied
Cast missile bulkhead	356-T6	None applied
Screen	5056 clad with 6253	Clear varnish
Extruded doubler	6061-T6	Clear lacquer

(a) Baking pans of these alloys may alternatively be chromate conversion coated prior to the application of silicone resin. (b) Thermosetting

- Rinsing
- Acidulated rinsing (recommended if supplementary coating is to be applied)
- Drying
- Application of a supplementary coating when required

Surface preparation entails the same procedures as are used in preparation for anodizing. However, the cleaning procedure for preparing aluminum for conversion coating is much more critical than for anodizing. After cleaning, removal of the natural oxide film is accomplished in any of the standard aqueous solutions, such as chromate-sulfate, chromate, or phosphate.

Pretreatment immediately prior to the coating operation is required for the development of extremely uniform conversion coatings. Either acid or alkaline solutions are used. Subsequent to the above operations, the work is subjected to the conversion coating solution. The addition of a wetting agent, such as sodium alkyl aryl sulfonate, to the solution helps to produce a uniform and continuous coating. After coating, the work is thoroughly rinsed and dried. The final rinse is usually hot (60 to 80 °C, or 140 to 180 °F) to aid drying. Drying is important in order to prevent staining. Drying at temperatures higher than 65 °C (150 °F) usually dehydrates the coatings and thus increases hardness and abrasion resistance.

Supplementary coatings of oil, wax, paint, or other hard organic coatings frequently are applied. If the conversion coating is intended to improve subsequent forming or drawing, the final supplementary coating may be soap or a similar dry-film lubricant.

Oxide Coating Processes. The modified Bauer-Vogel (MBV), Erftwerk (EW), and Alrok processes are the principal methods for applying oxide-type conversion coatings. Nominal compositions of the solutions used and typical operating conditions are given in Table 17. The MBV process is used on pure aluminum as well as on aluminum-

Table 17 Process conditions for oxide conversion coating of aluminum

Process	Bath composition	Amount g/L	Amount oz/gal	Temperature °C	Temperature °F	Duration, min	Uses
I MBV	Sodium chromate	15	1.7	96	205	5-10 or	Corrosion protection or foundation for
	Sodium carbonate	50	5.7			20-30	varnishes or lacquers
II MBV	Sodium chromate	15	1.7	65	150	15-30	In situ treatment of large objects with paint
	Sodium carbonate	50	5.7				brush or spray. When 8 g/L (0.9 oz/gal)
	Sodium hydroxide	4	0.5				sodium hydroxide is added, MBV
							oxidation may be carried out at 35 °C
							(95 °F) for 30 min
EW	Sodium carbonate	56	6.4	88-100	190-212	8-10	For copper-containing alloys
	Sodium chromate	19	2.2				
	Sodium silicate	0.75-4.5	0.09-0.5				
Alrok	Sodium carbonate	20	2.3	88-100	190-212	20	Final treatment for aluminum products
	Potassium dichromate	5	0.6				

magnesium, aluminum-manganese, and aluminum-silicon alloys. The coating produced varies from a lustrous light gray to a dark gray-black color. The EW process is used for alloys containing copper. The film produced is usually very light gray. The Alrok process is for general-purpose use with all alloys, and it is often the final treatment for aluminum products. Coatings vary in color from gray to green and are sealed in a hot dichromate solution.

Phosphate Coating Process. The range of operating conditions and a formula for a standard solution for phosphate coating are given below:

Specific formulations	
Ammonium dihydrogen phosphate $(NH_4H_2PO_4)$	61.7%
Ammonium bifluoride (NH_4HF_2)	22.9%
Potassium dichromate $(Kr_2Cr_2O_7)$	15.4%
Operating temperature	45-50 °C (110-120 °F)
Treatment time	1-5 min
Desired operating range	
Phosphate ion	20-100 g/L (2.6-13.2 oz/gal)
Fluoride ion	2-6 g/L (0.26-0.80 oz/gal)
Dichromate ion	6-20 g/L (0.80-2.6 oz/gal)
Operating temperature	18-50 °C (65-120 °F)
Treatment time	1.5-5 min

Each liter (gallon) of solution contains 75 to 150 g (10 to 20 oz) of a mixture consisting of the above formulations (U.S. Patent 2,494,910, 1950).

Phosphate coatings vary in color from light bluish-green to olive green, depending on the composition of the aluminum-base material and the operating conditions of the bath. The phosphate-chromate conversion coatings are used extensively on aluminum parts or assemblies to provide galvanic protection from components of different kinds of materials, such as bushings or inserts made of steel.

Chromate Coating Process. Solution compositions and operating conditions for two chromate conversion coating processes are given in Table 18. Chromate coatings vary from clear and iridescent to light yellow or brown, depending on the composition of the aluminum-base material and the thickness of the film. Chromate coatings are used when maximum resistance to corrosion is desired.

Chromate coatings exhibit low electrical resistivity. At a contact pressure of 1380 kPa (200 psi),

in a direct-current circuit, the resistivity of a normal chromate film varies from 0.30 to 3.0 $\mu\Omega/mm^2$ (200 to 2000 $\mu\Omega/in.^2$). This resistivity is low enough so that a chromate-coated article can be used as an electrical ground. The conductivity of the films at radio frequencies is extremely high. This permits the use of a chromate film on electrical shields and wave guides. Thus, chromate conversion coating is widely used for treatment of aluminum articles for the electronics industry.

Processing equipment for conversion coating solutions must be made from acid-resistant materials. Tanks may be made of type 316 stainless steel or of low-carbon steel if lined with polyvinyl chloride or another suitably protective material. Tanks for solutions that do not contain fluorides can be constructed of acid-resistant brick or chemical stoneware. Racks can be made of low-carbon steel but must be coated with an acid-resistant compound. Heating coils or electrical immersion heaters should be made of stainless steel or stainless-clad material.

Some conversion coating solutions cause a sludge to form in the bottom of the tank. To prevent contact between the sludge and the workpieces, the tank may be equipped with a false bottom through which sludge can fall.

Adequate ventilation must be provided to remove vapors. The inhalation of fluoride vapors is dangerous. Solutions should not contact the skin; if they do, the affected area should be washed immediately with running water and then be treated by a physician. Respirators, goggles, and gloves should be worn when handling all chemicals used to make up solutions. Brushes used to apply solutions should have natural bristles; synthetic bristles are attacked by solutions.

Control of Solution. Most users of conversion coating solutions purchase prepared formulations for makeup and solution adjustment. In general, the solutions require control of both pH and the concentration of the critical elements. Direct measurement of pH is made with a glass-cell electric pH meter. The percentage concentration of active ion is obtained by direct titration with a suitable base.

Solution control becomes more critical as the size of the bath decreases with respect to the amount of work treated. Experienced operators of a conversion coating process can detect changes

Table 18 Process conditions for chromate conversion coating of aluminum

Process	Solution composition	Amount g/L	Amount oz/gal	pH	Temperature °C	Temperature °F	Treatment time
Process A(a)	CrO3	6(b)	0.80(b)	1.2-2.2	16-55	60-130	5 s-8 min
	NH4HF2	3	0.40				
	SnCl4	4	0.6				
Process B(c)	Na2Cr2O7 · 2H2O	7(b)	1(b)	1.2-2.2	16-55	60-130	5 s-8 min
	NaF	1	0.1				
	K3Fe(CN)6	5	0.7				
	HNO3 (48° Bé)	(d)	(d)				
Process C(e)	H3PO4	64	8.5	1.2-2.2	40-80	105-175	1-10 min
	NaF	5	0.6				
	CrO3	10	1.3				

(a) U.S. Patents 2,507,959 (1950) and 2,851,385 (1958). (b) Desired range of hexavalent chromium ion, 1 to 7 g/L (0.13 to 0.90 oz/gal). (c) U.S. Patent 2,796,370 (1957). (d) 3 mL (0.1 fluid oz). (e) Process for Alodine, Alochrome, and Bonderite

in the composition of the solution by observing the color and appearance of the treated work. A skilled operator often can control the bath by this method alone.

During use, coating solutions are depleted by drag-in, drag-out, and consumption of the basic chemicals. In one plant, drag-in of alkaline cleaner into the conversion coating bath adversely affected the appearance of the conversion coating. Details of this problem and the method adopted for correcting it are given in the following example.

Aluminum screen cloth made from wires of alloy 5056 clad with alloy 6253 had a rejection rate as high as 3% because of the presence of sparklers on the product after chemical conversion coating. Sparklers, also known as shiners, are areas that have higher metallic reflectance than the rest of the conversion-coated surface; they are merely an appearance defect and do not affect the adherence of organic coatings. The following processing cycle was being used:

1. Alkaline cleaning for 1 min in an inhibited solution at 70 °C (160 °F)
2. Rinsing for 30 s in overflowing cold water
3. Conversion coating for 2½ min in a phosphate-chromate solution at 40 to 45 °C (100 to 115 °F)
4. Rinsing for 30 s in overflowing cold water
5. Second rinsing for 30 s in overflowing cold water
6. Drying
7. Application of a clear varnish (baked at 135 °C, or 275 °F for 1½ to 2 min) or of a gray pigmented paint. (For material to be painted, conversion coating required only 1½ min.)

The coating defects were found to be caused by contamination (and neutralization) of the acid conversion coating solution by drag-in from the alkaline cleaner. The use of a rotating beater to shake droplets of cleaning solution out of the screen openings had reduced drag-out from that bath, but it had not eliminated it.

To prevent neutralization of the acid conversion coating solution by contamination with alkali from step 1, the slightly acid overflow from the rinse in step 4 was piped back into the rinse tank in step 2, thus keeping it slightly acid. Re-

jects were eliminated. This procedure also reduced the amount of overflow rinse water needed to operate the line.

Control of Coating Quality. A properly applied coating should be uniform in color and luster and should show no evidence of a loose or powdery surface. Poor luster or powder surfaces are caused by low pH, improper cleaning and rinsing, excessive treatment temperature or treatment time, a contaminated bath, or insufficient agitation. Light and barely visible coatings are caused by high pH, low operating temperatures, insufficient treatment times, or high ion concentrations. Usually, the quality of a conversion coating is established on the basis of its appearance, corrosion resistance, hardness, and adherence. These qualities may be determined by the ASTM test methods described in the standards listed below:

Corrosion resistance

- Salt spray: B 117
- Copper-accelerated acetic acid salt spray (fog): B 368
- Evaluation of painted or coated specimens subjected to corrosive exposure: D 1654

Resistance to blistering

- Evaluation of blistering of paints: D 714

Adherence

- Elongation of attached organic coatings with conical mandrel apparatus: D 522

Hexavalent chromium compounds are especially effective components of solutions that form conversion coatings on aluminum. However, environmental regulations often make the handling of chromate-containing rinses a high-cost operation. Two types of technology address this problem. One is a dried-in-place chromate coating system, which eliminates the need for subsequent rinsing. The second involves the use of chromium-free treatments that form oxide films containing selected metal ions. The use of either of these processes, when possible, eliminates the need for expensive chrome destruction.

Electroplating

Aluminum-base materials are more difficult to electroplate than the common heavier metals because aluminum has a high affinity for oxygen, which results in a rapidly formed, impervious oxide film, and because most metals used in electroplating are cathodic to aluminum, so that voids in the coating lead to localized galvanic corrosion. Following are comparisons between the electrolytic potentials of several common metals and those of pure aluminum:

Metal	Potential, mV(a)
Magnesium	–850
Zinc	–350
Cadmium	–20 to 0
Aluminum (pure)	0
Aluminum-magnesium alloys	+100
Aluminum-copper alloys	+150
Iron, low-carbon steel	+50 to 150
Tin	+300
Brass	+500
Nickel	+500
Copper	+550
Silver	+700
Stainless steel	+400 to 700
Gold	+950

Note: Metals above aluminum in this list will protect it; those below cause aluminum to corrode preferentially. Cathode and anode polarization, however, can cause a reversal of these relationships. (a) In a 6% sodium chloride solution. Source: *Metal Finishing*, Nov 1956

Electrodeposits of chromium, nickel, cadmium, copper, tin, zinc, gold, or silver are used for various decorative and functional applications. For example, automotive aluminum bumpers get a zincate treatment, copper strike, and a plating of copper, nickel, and chromium. A copper strike coated with cadmium and chromate or by flowed tin enables the soft soldering of electrical terminals to an aluminum chassis. Brass enhances the bonding of rubber to aluminum. Silver, gold, and rhodium provide specific electrical and electronic surface properties. Examples of applications of plated aluminum with typical finishing sequences are given in Table 19.

Effect of Substrate Characteristics on Plating Results. Each aluminum alloy, according to its metallurgical structure, behaves differently from others during electroplating. Alloying elements may be in solid solution in the aluminum, or they may be present in discrete particles or as intermetallic compounds. These microconstituents have different chemical or electrochemical reactivities, and their surfaces do not respond uniformly to treatment. Variations in response also occur between different lots or product forms of the same alloy.

Surface Preparation Methods. The three established methods for surface preparation prior to electroplating are surface roughening, anodizing, and immersion coating in zinc or tin solutions.

Surface roughening, which is accomplished either by mechanical abrasion or by chemical etching, assists in mechanically bonding the electrodeposits to the aluminum surface. Surface roughening is sometimes used in preparation for

Table 19 Applications using electroplated coatings on aluminum products

Product	Form	Preplating treatment	Electroplating system	Thickness μm	mils	Reason for plating
Automotive applications						
Bearings	Sheet	None	Pb-Sn-Cu alloy	6-32	0.25-1.25	Prevent seizing
Bumper guards	Castings	Buff and zincate	Cu + Ni + Cr	2.5 + 51 + 0.8	0.1 + 2 + 0.03	Appearance; corrosion resistance
Lamp brackets; steering-column caps	Die castings	Buff and zincate	Cu + Ni + Cr	0.8 + 20 + 1.3	0.03 + 0.8 + 0.05	Appearance; corrosion resistance
Tire molds	Castings	None	Hard Cr	51	2	Appearance; corrosion resistance
Aircraft applications						
Hydraulic parts; landing gears; small engine pistons	Forgings	Machine and zincate	Cu flash + Cu + hard Cr	2.5 + 25 + 76	0.1 + 1 + 3	Wear resistance
Propellers	Forgings	Conductive rubber coating	Ni	203	8	Resistance to corrosion and erosion
Shell	Extrusion	Double zincate	Cu flash + Cd(a)	8-13(a)	0.3-0.5(a)	Dissimilar-metal protection
Electrical and electronics applications						
Busbars; switchgears	Extrusions	Zincate	Cu flash + Cu + Ag(b)	8 + 5(b)	0.3 + 0.2(b)	Nonoxidized surface; solderability; corrosion resistance
Intermediate-frequency housings	Die castings	Zincate	Cu flash + Cu + Ag + Au(c)	13 + 13 + 0.6(c)	0.5 + 0.5 + 0.025(c)	Surface conductivity; solderability; corrosion resistance
Microwave fittings	Die castings	Zincate	Cu flash + Cu + Ag + Rh	0.25 + 13 + 0.5	0.01 + 0.5 + 0.02	Smooth, nonoxidized interior; corrosion resistance of exterior
Terminal plates	Sheet	Zincate	Cu flash	...	...	Nonoxidized surface; solderability; corrosion resistance
General hardware						
Screws; nuts; bolts	Castings	Buff and zincate	Cd (on threads)	13; 0.5 on threads	0.5; 0.2 on threads	Corrosion resistance
Die cast spray guns and compressors	...	Buff and zincate	Hard Cr	51	2	Appearance
Die cast window and door hardware	...	Barrel burnish and zincate	Brass(d)	8(d)	0.3(d)	Appearance; low cost
Household appliances						
Coffee maker	Sheet	Buff and zincate	Cr	5	0.2	Appearance; cleanness; resistance to food contamination
Refrigerator handles; salad makers; cream dispensers	Die castings	Buff and zincate	Cu + Ni + Cr	2.5 + 13 + 0.8	0.1 + 0.5 + 0.03	Appearance; cleanness; resistance to food contamination
Personal products						
Compacts; fountain pens	Sheet	Buff and zincate	Cu flash + brass	5	0.2	Appearance; low cost
Hearing aids	Sheet	Zincate	Cu flash + Ni + Rh	19 + 0.25	0.75 + 0.01	Nonoxidizing surface; low cost
Jewelry	Sheet	Buff and zincate	Brass + Au	8 + 0.25	0.3 + 0.01	Appearance; low cost

(a) Chromate coating applied after cadmium plating. (b) Soldering operation follows silver plating. (c) Baked at 200 °C (400 °F) after copper plating and after silver plating. Soldering operation follows gold plating. (d) Brass plated in barrel or automatic equipment

the application of hard chromium to aluminum engine parts, such as pistons. A water blast of fine quartz flour may be used to remove surface oxides and to abrade the surface. The adherent wet film protects the aluminum surface from further oxidation before plating. The quartz film is dislodged by the evolution of hydrogen that occurs during plating. Chemical etching produces undercut pits that provide keying action for the electrodeposited metal. In general, mechanical bonding of electrodeposits is not reliable, particularly for applications involving temperature variations. Therefore, preparation by surface roughening is not recommended.

Anodizing is sometimes used as a method of surface preparation prior to electroplating. However, the adherence of the subsequent electrodeposit is limited; plated deposits over anodic films are highly sensitive to surface discontinuities, making the time, temperature, and current density of the anodizing process critical. Phosphoric acid anodizing has been used for the aluminum alloys listed in Table 20; the sequence of operations is:

1. Vapor degreasing or solvent cleaning
2. Mild alkaline cleaning
3. Rinsing

4. Etching for 1 to 3 min in a solution containing sodium carbonate (23 g/L, or 3 oz/gal) and sodium phosphate (23 g/L, or 3 oz/gal), at 65 °C (150 °F)
5. Rinsing
6. Dipping in nitric acid solution (50% HNO_3 by volume) at room temperature
7. Rinsing
8. Phosphoric acid anodize according to the conditions given in Table 20; the anodic coating should not be sealed.
9. Rinsing
10. Electroplating in a copper pyrophosphate or nickel sulfamate bath

Immersion coating in a zincate solution is a traditional method of preparing aluminum surfaces for electroplating. It is simple and low in cost, but it is also critical with respect to surface pretreatment, rinsing, and the strike sequence used. The principle of zincating is one of chemical replacement, whereby aluminum ions replace zinc ions in an aqueous solution of zinc salts. Thus, a thin, adherent film of metallic zinc is deposited on the aluminum surface. Adhesion of the zinc film depends almost entirely on the metallurgical bond between the zinc and the aluminum. The quality and adhesion of subsequent electrodeposits depend on obtaining a thin, ad-

Table 20 Conditions for anodizing aluminum alloys prior to electroplating

Electrolyte solution of aqueous H_3PO_4

Alloy(a)	Specific gravity	Temperature °C	°F	Voltage	Time, min
1100	1.300	30	87	22	5
3003	1.300	29	85	22	5
5052	1.300	29	85	22	10
6061	1.300	29	85	22	7

(a) With special care, phosphoric acid anodizing may be used also for aluminum-copper or aluminum-silicon alloys. Source: Wittlock, Tech. Proc. AES, Vol 48 (No. 52), 1961

herent, and continuous zinc film. The electrolytic Alstan strike is coming into general use as a more dependable method than the zincate process for obtaining good adhesion. It is followed by a bronze strike.

Another immersion process is based on the deposition of tin from a stannate solution. This offers improved corrosion resistance because of the more favorable electrolytic potential of tin versus zinc in chloride solutions.
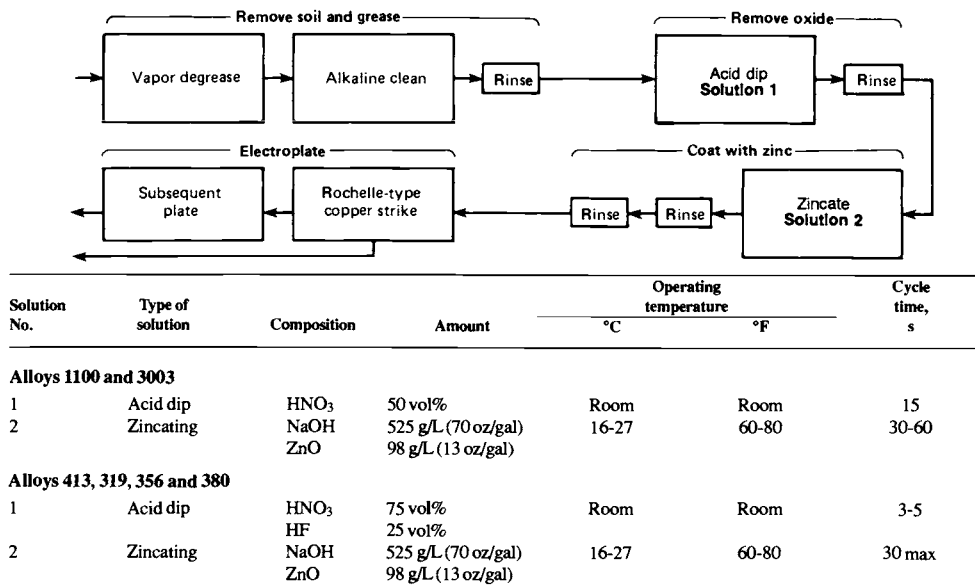
Fig. 4 Preplating surface preparation procedures suitable for wrought aluminum alloys that contain high amounts of silicon or do not contain interfering microconstituents (e.g., 1100 and 3003) and for aluminum casting alloys 413, 319, 356, and 380
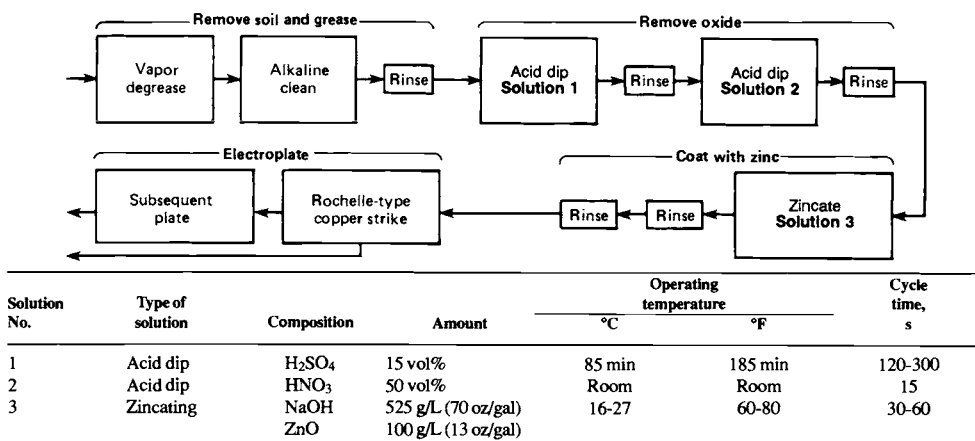
Solution No.	Type of solution	Composition	Amount	Operating temperature °C	Operating temperature °F	Cycle time, s
Alloys 1100 and 3003						
1	Acid dip	HNO₃	50 vol%	Room	Room	15
2	Zincating	NaOH	525 g/L (70 oz/gal)	16-27	60-80	30-60
		ZnO	98 g/L (13 oz/gal)			
Alloys 413, 319, 356 and 380						
1	Acid dip	HNO₃	75 vol%	Room	Room	3-5
		HF	25 vol%			
2	Zincating	NaOH	525 g/L (70 oz/gal)	16-27	60-80	30 max
		ZnO	98 g/L (13 oz/gal)			

Fig. 5 Preplating surface preparation procedures suitable for all wrought aluminum alloys, for most aluminum casting alloys, and for magnesium-containing aluminum alloys with interfering microconstituents. Applicable alloys include 1100, 3003, 3004, 2011, 2017, 2024, 5052, 6061, 208, 295, 319, and 355.

Solution No.	Type of solution	Composition	Amount	Operating temperature °C	Operating temperature °F	Cycle time, s
1	Acid dip	H₂SO₄	15 vol%	85 min	185 min	120-300
2	Acid dip	HNO₃	50 vol%	Room	Room	15
3	Zincating	NaOH	525 g/L (70 oz/gal)	16-27	60-80	30-60
		ZnO	100 g/L (13 oz/gal)			

Immersion Procedures. To obtain consistently good results with zinc or tin immersion procedures, it is essential that cleaning and conditioning treatments produce a surface of uniform activity for deposition. Vapor degreasing or solvent cleaning followed by alkaline cleaning is used for removing oil, grease, and other soils. The alkaline cleaner may be a mild etching solution of water containing 23 g/L (3 oz/gal) each of sodium carbonate and sodium phosphate. The solution temperature should range from 60 to 80 °C (140 to 180 °F), and the material should be immersed for 1 to 3 min and then be thoroughly rinsed. After cleaning, the material is further treated to remove the original oxide film as well as any microconstituents that may interfere with the formation of a continuous film or that may react with the subsequent plating solutions.

Castings present special problems, because their surfaces are more porous than those of wrought products. Solutions entrapped in pores are released during subsequent processing, resulting in unplated areas, staining, or poor adhesion of the electrodeposit. Sometimes the trapped solutions become evident much later, during storage or further processing (such as heating for soldering). Furthermore, even if pores are free of solution, the deposit may not bridge them, thus creating a point of attack for corrosion of the base metal. This is of particular significance in the electroplating of aluminum castings: The electrodeposited metal is electrolytically dissimilar to aluminum, and thus every opening in a casting surface will be a source of corrosion. To circumvent these problems, it is essential when preparing cast aluminum surfaces for electroplating that all processing steps be carefully controlled to avoid surfaces with excessive porosity.

In zincating, the procedures used for removal of the original oxide film and for application of a zinc film depend to a considerable degree on the aluminum alloy. Several methods are available for accomplishing this surface conditioning, and some alloys can be conditioned by more than one procedure. In such instances, the order of preference follows the order of discussion of these procedures in the following paragraph.

Wrought alloys without interfering microconstituents and casting alloys containing high silicon are prepared for electroplating according to the procedure shown by the flow chart in Fig. 4. The flow chart in Fig. 5 represents the procedure for alloys that contain interfering microconstituents; this procedure is suitable for all wrought alloys, most casting alloys, and especially aluminum-magnesium alloys. Figure 6 indicates the procedure for treating most casting alloys, wrought alloys that contain less than approximately 3% Mg, and alloys of unknown composition.

Table 21 gives details of three zincating solutions that may be used alternatively to the solution indicated in the tables that accompany Fig. 4 to 6. The modified solution in Table 21 is recommended when double-immersion zincating (Fig. 6) is required; it is not essential for alloys 2024 and 7075. This solution produces more uniform coverage than the unmodified solution and also imparts greater corrosion resistance to the treated work. Dilute solution No. 1 in Table 21 is recommended when there are problems in rinsing and drag-out. Dilute solution No. 2 provides a greater reserve of zinc for high-production operations, but at a slight sacrifice in effectiveness of rinsing. In some special operations, triple zincate treatment is used. This involves essentially stripping the second zinc film formed in double zincate and adding a zincate from a third solution. Triple zincate provides an even more uniform and fine-grain zinc coating than double zincate.

If correct procedures are followed, the resulting zinc deposit is uniform and firmly adherent to the aluminum surface. The appearance of the surface will vary with the alloy being coated, as well as with the rate at which the coating forms. The weight of zinc deposit should be from 1.5 to 5.0 mg/dm² (0.1 to 0.3 mg/in.²). Generally, it is desirable to limit the deposit to 3 mg/dm² (0.2 mg/in.²).

The thinner and more uniform zinc deposits are the most suitable for plating preparation and for the service performance of plated coatings. Heavy zinc deposits usually are spongy, less adherent, and undesirable from the standpoint of corrosion resistance.

Plating Procedures. Copper is one of the easiest metals to electrodeposit on zincated aluminum surfaces. For this reason, it is used extensively as an initial strike over which other metals may be subsequently deposited. An advantage of the copper strike is that it protects the thin zinc film from attack by the plating solutions. Penetration of the zinc film and attack of the underlying aluminum surface by the plating solutions result in a poorly bonded electrodeposit.

The copper strike bath should be a Rochelle-type copper cyanide solution. The composition
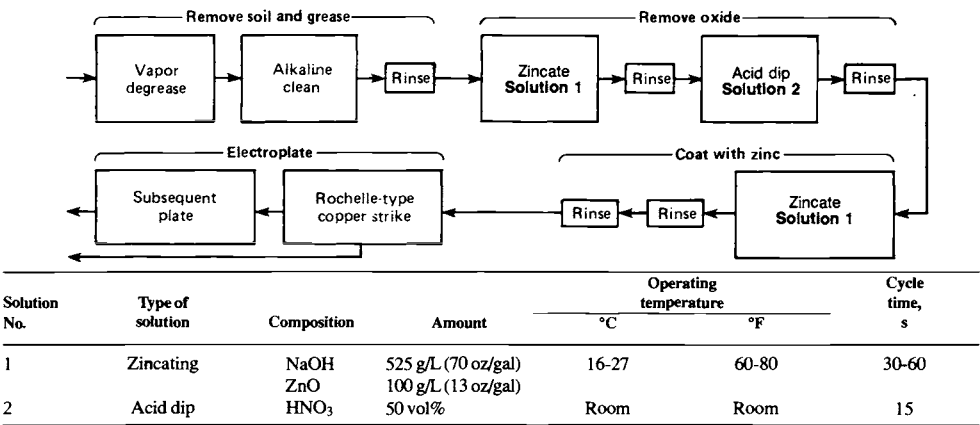
Solution No.	Type of solution	Composition	Amount	Operating temperature °C	°F	Cycle time, s
1	Zincating	NaOH	525 g/L (70 oz/gal)	16-27	60-80	30-60
		ZnO	100 g/L (13 oz/gal)			
2	Acid dip	HNO₃	50 vol%	Room	Room	15

Fig. 6 Preplating surface preparation procedures suitable for most aluminum casting alloys, for wrought aluminum alloys containing less than approximately 3% Mg (e.g., 1100, 3003, 3004, 2011, 2017, 2024, 5052, and 6061), and for aluminum alloys whose identities are not known

and operating conditions recommended for this bath are:

Copper cyanide	4 g/L (5.5 oz/gal)
Total sodium cyanide	50 g/L (6.5 oz/gal)
Free sodium cyanide	4 g/L (0.5 oz/gal) max
Sodium carbonate	30 g/L (4.0 oz/gal)
Rochelle salt	60 g/L (8.0 oz/gal)
Operating temperature	40-55 °C (100-130 °F)
pH	Varies with alloy; see Table 22

A brass strike is sometimes used in place of copper; however, a bronze strike is frequently used on a tin immersion coating. Table 22 gives operating conditions for the electrodeposition of different metals on zincated aluminum surfaces. Environmental considerations sometimes necessitate substitution for cyanide-containing solutions. Nickel strikes, which are successful as a result of careful control of composition and operation conditions, permit this.

Immersion Plating

Immersion plating refers to processes in which another metal is deposited from solution on an aluminum surface under the influence of the potential that exists between the solution and the immersed aluminum material. An external potential is not required. Deposits produced by immersion plating are thin and of little protective value.

Zincating, the procedure used for coating aluminum surfaces with zinc prior to electroplating (see the preceding section), is an example of immersion plating. Brass deposits can be produced by adding copper compounds to the sodium zincate solutions used in zincating.

Tin can be deposited from solutions containing potassium stannate, stannous chloride, or stannous sulfate-fluoride. The lubricating qualities of these tin deposits are desirable for aluminum alloy piston and engine components. Immersion tin coatings also are used to facilitate soft soldering and as a base coating for building up electrodeposits. The composition and operating conditions of a successful immersion tin bath are given below:

Potassium stannate	100 g/L (13.40 oz/gal)
Zinc acetate	2 g/L (0.27 oz/gal)
m-Cresol sulfonic acid	35 g/L (4.40 oz/gal)
Temperature of solution	60 °C (140 °F)
Immersion time	2 min

Degreasing is the only pretreatment required. The thickness of the tin coating is about 1.3 μm (0.05 mil); solution life is about 0.75 m²/L (30 ft²/gal).

Electroless Plating

Electroless plating, often called chemical plating, refers to nonelectrolytic processes that in-

volve chemical reduction, in which the metal is deposited in the presence of a reducing agent. Deposition may take place on almost any type of material, even the container of the solution. For a variety of applications in the aircraft industry, nickel is chemically plated on aluminum parts of shapes for which electroplating is not practical. However, electroless plating is too expensive to be used when conventional electroplating is feasible. The composition and operating conditions of a bath for the successful deposition of nickel are given below:

Nickel chloride	30 g/L (4 oz/gal)
Sodium hypophosphite	7.5 g/L (1 oz/gal)
Sodium citrate	72 g/L (9.60 oz/gal)
Ammonium chloride	48 g/L (6.40 oz/gal)
Ammonium hydroxide (0.880 sp gr)	13 g/L (1.75 oz/gal)
pH	10
Temperature of solution	80-90 °C (180-190 °F)
Immersion time	1 h

Deposits produced contain about 6 wt% P and usually are not considered suitable as a base for chromium plate. The immersion time given is for deposits 50 μm (2 mil) or more thick.

Silver can be plated using the electroless process on anodized aluminum-base materials. The procedure consists of degreasing the anodized surface, dipping in dilute hydrochloric acid, water rinsing, and then immersing the object in a silvering solution. A mixture of two solutions is required for silvering. The first consists of 3.33 mL (0.113 fluid oz) of a 10% solution of silver nitrate to which a 7.5 vol% solution of ammonium hydroxide is added until the precipitate first formed just redissolves, after which an excess of 40 mL (1.3 fluid oz) of ammonium hydroxide solution is added. The second solution is made by adding 80 g (3 oz) of Rochelle salt or 40 g (1.4 oz) of potassium citrate to water, to a total volume of 330 mL (11 fluid oz). Solutions are filtered and mixed immediately before use.

Additional information on electroless plating processes is available in the Section "Plating and Electroplating" in this Volume.

Painting

The difference between painting of aluminum and painting of iron or steel lies primarily in the method of surface preparation. Aluminum is an excellent substrate for organic coatings if the sur-

Table 21 Zincating solutions for use with aluminum alloys

Solution type	Sodium hydroxide g/L	oz/gal	Zinc oxide g/L	oz/gal	Ferric chloride crystals g/L	oz/gal	Rochelle salt g/L	oz/gal	Sodium nitrate g/L	oz/gal	Operating temperature °C	°F	Processing time, s
Modified(a)	525	70	100	13	1.00	0.13	9.8	1.3	...	...	15-27	60-80	30-60
Dilute 1(b)	50.3	6.7	5	0.7	2.03	0.30	50	6.7	0.98	0.13	21-24	70-75	30 max
Dilute 2(b)	120	16	20	2.7	2.03	0.30	50	6.7	0.98	0.13	21-24	70-75	30 max

(a) U.S. Patent 2,676,916 (1954). (b) U.S. Patents 2,676,916 (1954) and 2,650,886 (1953)

Table 22 Conditions for electroplating various metals on zincated aluminum surfaces

Electroplate	Minimum deposit μm	mils	Plating time, min	Bath temperature °C	°F	Current density A/dm²	A/ft²	Type of electrolyte
Copper:								
1 Copper strike(a)	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Brass strike(a)	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Copper plate(d)	12.5	0.5	40 s-2 min	76-83	170-180	3-6	30-60	High-speed NaCN or KCN
Brass	12.5	0.5	3-5	27-32	80-90	1	10	Cyanide
Cadmium:								
1 Copper strike(a)	12.5	0.5	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Cadmium plate	12.5	0.5	8-20	21-35	70-95	1.4-4.5	14-45	Cyanide
Chromium, decorative:								
1 Copper strike(a)	7.5	0.3	2(b)	34-54	100-130	2.4	24(b)	Rochelle cyanide(c)
2 Brass strike(a)	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Nickel undercoat	2.5-5	0.1-0.2	(e)	(e)	(e)	(e)	(e)	(e)
4 Chromium plate	25-50	0.01-0.02	10-12	43-46	110-115	0.07-0.15	0.7-1.5	Conventional
Chromium, decorative (direct on zincate)	0.75	0.03	5-10	18-21	65-70	0.07-0.15	0.7-1.5	Conventional
Chromium, hard:								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Chromium plate	1.25	0.05	5	54	130	0.07-0.15	0.7-1.5	Conventional
Chromium, hard (direct on zincate)	1.25	0.05	10-20; then 54(f)	18-21; then 130(f)	65-70	0.07-0.15; then 0.3(f)	0.7-1.5; then 3 A in.²	Conventional
Chromium, hard (for corrosion protection):								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24	Rochelle cyanide(c)
2 Brass strike	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Nickel undercoat	25-50	1-2	(e)	(e)	(e)	(e)	(e)	(e)
4 Chromium plate	2.5-5	0.1-0.2	10-12	43-46	110-115	0.07-0.15	0.7-1.5	Conventional
Gold:								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Brass strike	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Nickel undercoat	17.5	0.7	(e)	(e)	(e)	(e)	(e)	(e)
4 Gold plate	0.625	0.025	10 s-1 min	49-71	120-160	0.5-1.5	5-15	Potassium cyanide
Nickel (for minimum corrosion protection):								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Brass strike	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Nickel plate	7.5-12.5	0.3-0.5	(e)	(e)	(e)	(e)	(e)	(e)
Nickel (for maximum corrosion protection):								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Brass strike	7.5	0.3	2-3	27-32	80-90	0.5	5	Cyanide
3 Nickel plate	25-50	0.3-0.5	(e)	(e)	(e)	(e)	(e)	(e)
Silver:								
1 Double silver strike	0.625	0.025	10 s(g)	30(g)	80(g)	1.5-2.5(g)	15-25(g)	Cyanide(h)
2 Silver plate	1.25-2.5	0.05-0.1	18-35	27-32	80	0.5	5	Cyanide
Silver (alternative method):								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Silver strike	0.50	0.02	10 s	27-32	80	1.5-2.5	15-25	Cyanide(j)
3 Silver plate	1.25-2.5	0.05-0.1	18-35	27-32	80	0.5	5	Cyanide
Tin:								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Tin plate(k)	17.5	0.7	15-30	93-99	200-210	4.5-6.5	45-65	Sodium stannate
Zinc:								
1 Copper strike	7.5	0.3	2(b)	34-54	100-130	2.4(b)	24(b)	Rochelle cyanide(c)
2 Zinc plate	12.5	0.5	18-45	24-30	75-86	1-3	10-30	Pyrophosphate
Zinc (direct on zincate)	12.5	0.5	10	24-35	75-95	0.5-5(m)	5-50(m)	Pyrophosphate

(a) An initial cyanide copper strike is generally used to achieve complete metal coverage of zincated aluminum parts prior to plating, because of the excellent throwing power of the copper electrolyte. A copper strike is not, however, recommended as the initial coating for alloys 5056, 214, 218, and others that contain substantial amounts of magnesium; these will achieve a better initial coverage in a brass strike. Neither copper strike nor brass strike should be used as a final finish; both should always have an electroplated top coat. (b) The copper strike is achieved during the first 2 min while the current density of the electrolyte is maintained at 2.4 A/dm² (24 A/ft²). Instead of being transferred from the strike bath to a high-speed sodium or potassium electrolyte for subsequent copper plating, the work may be allowed to remain (3 to 5 min) in the Rochelle-type electrolyte to be copper plated, provided the current density is lowered to 1.2 A/dm² (12 A/ft²). (c) Colorimetric pH of electrolyte is 12.0 for all treatable alloys except 5052, 6061, and 6063, for which pH is 10.2 to 10.5 (d) Work for which copper strike plating may be used may be left in the copper strike for copper plating, instead of being transferred to the high-speed sodium or potassium cyanide electrolyte (see footnote c). (e) As discussed in the article on nickel plating, various electrolytes are used, depending on the specific purpose of the plated deposit. If the nickel is to be deposited directly on the zincated surface, a bath must be selected that is suitable for application over zinc (examples of such baths are fluoborate and sulfamate nickel electrolytes). (f) The transition from low-temperature to high-temperature plating may be accomplished either by heating the electrolyte to 54 °C (130 °F) after deposition has started at 18 to 21 °C (65 to 70 °F) or by transferring the work (without rinsing) from an electrolyte at 18 to 21 °C (65 to 70 °F) to one at 54 °C (130 °F) and holding the work in the high-temperature electrolyte without current until the work reaches bath temperature. Current density is 0.07 to 0.15 A/dm² (0.7 to 1.5 A/in.²) in the electrolyte at 18 to 21 °C (65 to 70 °F). 1935 AS/mm² (3 A/in.²) at 54 °C (130 °F). (g) Each bath. (h) First strike bath contains 1 g (0.11 oz) of AgCN and 90 g (10.2 oz) of NaCN per litre (gallon); second bath, 5.3 g (0.60 oz) of AgCN and 67.5 g (7.7 oz) of NaCN per litre (gallon). (j) Contains 5.3 g (0.60 oz) of AgCN and 67.5 g (7.7 oz) of NaCN per litre (gallon). (k) After the aluminum material has been copper strike plated, tin may be applied also by immersion for 45 min to 1 h in a sodium stannate solution at 49 to 74 °C (120 to 165 °F). Time and temperature depend on solution used. (m) Current is applied as work is being immersed in electrolyte.

face is properly cleaned and prepared. For many applications, such as indoor decorative parts, the coating may be applied directly to a clean surface. However, a suitable prime coat, such as a wash primer or a zinc chromate primer, usually improves the performance of the finish coat.

For applications involving outdoor exposure, or for indoor applications that expose the part to impact or abrasive forces, a surface treatment such as ano-dizing or chemical conversion coating is required prior to the application of a primer and a finish coat. These processes were discussed above.

Anodizing in sulfuric or chromic acid electrolytes provides an excellent surface for organic coatings. Usually, only thin anodic coatings are required as a prepaint treatment. Decorative parts for home appliances generally are anodized before painting to ensure good paint adhesion over an extended period. Sulfuric acid anodic coatings are used when painting of only part of the surface is required for decorative effects; the anodic coating protects the unpainted portions of the surface.

Conversion coatings usually are less expensive than anodic coatings, provide a good base for paint, and improve the life of the paint by retarding corrosion of the aluminum substrate material. Adequate coverage of the entire surface by the

Table 23 Melted-oxide compositions of frits for porcelain enameling of aluminum

Constituent	Composition, wt%		
	Lead-base enamel	Barium enamel	Phosphate enamel
PbO	14-45	...	...
SiO$_2$	30-40	25	...
Na$_2$O	14-20	20	20
K$_2$O	7-12	25	...
Li$_2$O	2-4	...	4
B$_2$O$_3$	1-2	15	8
Al$_2$O$_3$	...	3	23
BaO	2-6	12	...
P$_2$O$_5$	2-4	...	40
F$_2$	...	...	5
TiO$_2$	15-20	(a)	(a)

(a) TiO$_2$, 7 to 9 wt%, added to frit during mill preparation of the enamel slip

No.	Type	Composition of solution		Operating temperature		Cycle time, min
		Constituent	wt%	°C	°F	
1	Alkaline cleaner(a)	(b)	(b)	60-82	140-180	2-5
2	Oxide removal	Chromic acid	3.5	82	180	3-10
		Sulfuric acid	18.0			
3	Chromate dip	Chromic sulfate	0.2	Ambient		1-6
		Potassium dichromate	14.4			
		Sodium hydroxide	7.75			

(a) Vapor degreasing may be used instead of alkaline cleaning. (b) Either inhibited or mildly etching (uninhibited) cleaners can be used

Fig. 7 Process for preparing heat-treatable aluminum alloys for porcelain enameling

conversion coating is important for good paint bonding.

The article "Painting" in this Volume contains additional information on surface preparation, paint formulations, and application procedures.
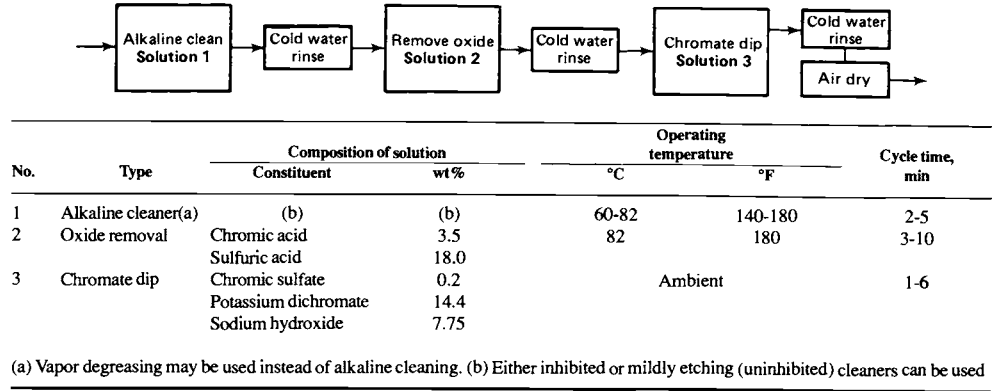
Porcelain Enameling

Porcelain enamels are glass coatings applied to products to improve appearance and protect the metal surface. Porcelain enamels are distinguished from other ceramic coatings by their predominantly vitreous nature and the types of applications for which they are used. They are distinguished from paint by their inorganic composition and the fusion of the coating matrix to the substrate metal.

Aluminum products, including tanks and vessels, architectural panels, cookware, and signs, may be finished by porcelain enameling to enhance appearance, chemical resistance, or weather resistance. The common porcelain enameling alloys for the various forms of aluminum are:

- *Sheet*: 1100, 3003, and 6061
- *Extrusions*: 6061
- *Casting alloys*: 443 and 356

Of the wrought alloys, only 6061 alloy is heat-treatable. Because of its higher strength, 6061 alloy has better handling characteristics before and during porcelain enameling, and it is stronger after porcelain enameling. The non-heat-treatable alloys are easier to form before porcelain enameling and are used for small parts for which the amount of distortion and low strength encountered after firing are acceptable. However, non-heat-treatable alloys are unsuitable for more than one coat of porcelain because of the crazing that occurs after a second firing.

Frits. The basic material of the porcelain enamel coating is frit, a special glass of small friable particles produced by quenching a molten glassy mixture. Because porcelain enamels are usually de-

signed for specific applications, the compositions of the frits from which they are made vary widely.

Enamel frits for aluminum are usually based on lead silicate and on cadmium silicate, but they may be based on phosphate or barium. Table 23 gives the compositions of several frits used for aluminum.

The high-lead enamels for aluminum have a high gloss, good acid and weather resistance, and good mechanical properties. The phosphate enamels generally are not alkali-resistant or water-resistant, but they may have good acid resistance. They melt at relatively low temperatures and are useful in many applications. The barium enamels are not as low-melting as the lead or phosphate glasses, but they do have good chemical durability.

Surface Preparation. The preparation of heat-treatable aluminum alloy parts for porcelain enameling involves the removal of soil and surface oxides and the application of a chromate coating. Figure 7 shows the sequence of these surface preparation treatments and gives operating conditions. Final drying removes all surface moisture; drying must be accomplished without contaminating the cleaned surface. Parts made of non-heat-treatable aluminum alloys require only the removal of soil, which can be done by alkaline cleaning or vapor degreasing.

Because enamel ordinarily is applied to aluminum to only about half the thickness to which it is applied to steel, freedom from surface scratches, burrs, and irregularities is doubly important for aluminum. Most shaping of aluminum is done before enameling, but the thin coating permits some bending, shearing, punching, and sawing of the enameled part.

Surfaces to be enameled should have generous inside radii of not less than 4.8 mm ($^3/_{16}$ in.) and outside radii of not less than 1.6 mm ($^1/_{16}$ in.). Attachments should be welded to the unenameled back side of enameled heavy-gage aluminum sheet or extrusions. The visible metal surfaces must not be overheated; overheating causes the aluminum to blister and alters the color and gloss of the enamel. Welding can be done before enameling, provided that the weld area is cleaned properly before coating.

Additives and Application. Porcelain enamel is usually applied to aluminum as a suspension of finely milled frit in water. Mill additions for wet process enamel frits for aluminum consist of boric acid, potassium silicate, sodium silicate, and other additives. These materials are used to control the wet suspension of the frits, and they contribute to the characteristics of the fired enamel. Titanium dioxide and ceramic pigments can also be added to produce opacity and the desired color, respectively.

Porcelain enamel slips for aluminum usually are applied by spraying, using either manual or automatic equipment with agitated pressure tanks. Slips for aluminum are not self-leveling and thus must be deposited smoothly in an even thickness and without runs or ripples.

Many aluminum parts are coated satisfactorily by the one-coat/one-fire method. Although the heat-treatable alloys can be recoated one or more times, the opacity and color of the coating will change with the thickness of the porcelain and with repeated firing. The desirable minimum fired enamel thickness is 65 μm (2.5 mil), and the desirable maximum is 90 μm (3.5 mil).

Furnaces. Forced convection is the preferred method of heating furnaces for firing porcelain enamel on aluminum. The heat is provided by electric package heaters, quartz-tube electric heaters, or metal-sheath heaters, all specially designed for operation at high ambient air temperature. Quartz-tube and metal-sheath heaters are adapted to the furnace so that radiant heat is available in the firing zone along with forced circulation. Package heaters are placed remote from the firing zone; this is the most effective method of eliminating direct radiation and hot spots. Heat imparted to the work from the package heater is derived completely from adequate air circulation to maintain a uniform temperature throughout the furnace of ±1% of the nominal operating temperature.

Forced-convection heating is also accomplished with gas-fired radiant tubes as the heat source. The tubes are baffled from the work or firing zone so that air circulation provides the same advantages as in electric-package forced-convection heating.

Furnace construction for aluminum enameling generally requires the use of stainless steel inner

Table 24 Cycles for firing porcelain enamel on aluminum

Type of part	Section thickness, 0.025 mm (0.001 in.)	Firing time, min	Firing temperature °C	Firing temperature °F
Any configuration	26-40	5-6½	540	1000
Any configuration	51-64	7-8	540	1000
Extrusions	125	10	550	1020
Extrusions	187 up	12-15	550	1020

liner sheets, low-density wall insulation, and plain-carbon steel exterior shell. This type of fabrication eliminates long heat-up and cool-down periods.

Firing of enamel on aluminum is accomplished between 525 and 550 °C (980 and 1020 °F); cycles are shown in Table 24. To control color and gloss of the enamel within acceptable limits, the temperature throughout the work must be held to 1.5 °C (2.5 °F).

Detailed information about porcelain enamel coatings is available in the article "Porcelain Enameling" in this Volume.

Shot Peening

Shot peening is a method of cold working in which compressive stresses are induced in the exposed surface layers of metallic parts by the impingement of a stream of shot, which is directed at the metal surface at high velocity under controlled conditions. It differs from blast cleaning in primary purpose and in the extent to which it is controlled to yield accurate and reproducible results. Cast steel shot is the most widely used peening medium, but glass beads often are used for peening aluminum and other metals that might be contaminated by steel shot.

Although shot peening cleans the surface being peened, this function is incidental. The major purpose of shot peening is to increase fatigue strength. For example, the fatigue strength of several aluminum alloys peened with cast steel

Table 25 Designations for aluminum finishes

Designation(a)	Finish	Designation(a)	Finish
Mechanical finishes—M		**Anodic coatings—A**	
As fabricated:		General:	
M10	Unspecified	A10	Unspecified
M11	Specular finish as fabricated	A11	Preparation for other applied coatings
M12	Nonspecular finish as fabricated	A12	Chromic acid coatings
M1X	Other (to be specified)	A13	Hard, wear- and abrasion-resistant coatings
Buffed:		A1X	Other (to be specified)
M20	Unspecified	Protective and decorative:	
M21	Smooth specular	(Less than 10 μm, or 0.4 mil)	
M22	Specular	A21	Clear (natural)
M2X	Other (to be specified)	A22	Integral color
Directional textured:		A23	Impregnated color
M30	Unspecified	A24	Electrolytically deposited color
M31	Fine satin	A2X	Other (to be specified)
M32	Medium satin	Architectural Class II(c):	
M33	Coarse satin	(10 to 18 μm, or 0.4 to 0.7 mil)	
M34	Hand rubbed	A31	Clear
M35	Brushed	A32	Integral color
M3X	Other (to be specified)	A33	Impregnated color
Nondirectional textured:		A34	Electrolytically deposited color
M40	Unspecified	A3X	Other (to be specified)
M41	Extra fine matte	Architectural Class I(c):	
M42	Fine matte	(18 μm, or 0.7 mil)	
M43	Medium matte	A41	Clear (natural)
M44	Coarse matte	A42	Integral color
M45	Fine shot blast	A43	Impregnated color
M46	Medium shot blast	A44	Electrolytically deposited color
M47	Coarse shot blast	A4X	Other (to be specified)
M4X	Other (to be specified)		
		Resinous and other organic coatings(d)—R	
Chemical finishes(b)—C		R10	Unspecified
Nonetched cleaned:		R1X	Other (to be specified)
C10	Unspecified		
C11	Degreased	**Vitreous (porcelain and ceramic) coatings(d)—V**	
C12	Inhibited chemical cleaned	V10	Unspecified
C1X	Other (to be specified)	V1X	Other (to be specified)
Etched:			
C20	Unspecified	**Electroplated and other metal coatings(d)—E**	
C21	Fine matte	E10	Unspecified
C22	Medium matte	E1X	Other (to be specified)
C23	Coarse matte		
C2X	Other (to be specified)	**Laminated coatings(d)—L**	
Brightened:		L10	Unspecified
C30	Unspecified	L1X	Other (to be specified)
C31	Highly specular		
C32	Diffuse bright		
C3X	Other (to be specified)		
Chemical coatings:			
C40	Unspecified		
C41	Acid chromate-fluoride		
C42	Acid chromate-fluoride-phosphate		
C43	Alkaline chromate		
C44	Nonchromate		
C45	Nonrinsed chromate		
C4X	Other (to be specified)		

(a) All designations are preceded by the letters "AA," to identify them as Aluminum Association designations. Examples of methods of finishing are given in the Aluminum Association publication from which the presentation here is derived. (b) Includes chemical conversion coatings, chemical or electrochemical brightening and cleaning treatments. (c) Classification established in Aluminum Association Standards for Anodically Coated Aluminum Alloys for Architectural Applications, October 1978. (d) These designations may be used until more complete series of designations are developed for these coatings.

shot can be improved by 23 to 34%. The process has other useful applications, such as relieving tensile stresses that contribute to stress-corrosion cracking (SCC), and forming and straightening metal parts.

Peening action improves the distribution of stresses in surfaces that have been disturbed by grinding, machining, or heat treating. Shot peening is especially effective in reducing the harmful stress concentration effects of notches, fillets, forging pits, surface defects, and the heat-affected zones of weldments.

The surface tensile stresses that cause SCC can be effectively overcome by the compressive stresses induced by shot peening with either steel shot or glass beads. In one application, test bars were cut in the short transverse direction from a 7075-T6 aluminum alloy hand forging and stressed to 75% of the yield strength. During alternate immersion tests in 3.5% sodium chloride solution, unpeened specimens failed in 1, 5, 17, and 28 days. Specimens peened in the unstressed condition with cast steel shot lasted 365 and 730 days, when failure occurred in the unpeened grip outside the test area. During exposure to an industrial atmosphere, similar unpeened test bars failed in 20, 37, 120, and 161 days, whereas a peened specimen under the same conditions was uncracked when it was removed from testing after an exposure of 8½ years.

Additional information is provided in the article "Shot Peening" in this Volume.

Designation System for Aluminum Finishes

Finishes used on aluminum are categorized as mechanical or chemical finishes or as coatings. Types of coatings that can be applied include anodic coatings, resinous and other organic coatings, and vitreous coatings. In addition, laminated, electroplated, or other metallic coatings can be used on aluminum.

In the designation system developed by the Aluminum Association, each of these categories is assigned a letter, and the various finishes in each category are designated by two-digit numerals. Specific finishes of the various types thus are designated by a letter followed by two numbers, as shown in Table 25. Two or more designations can be combined into a single designation to identify a sequence of operations covering all the important steps leading to a final complex finish.

When designations for chemical coatings are used alone, other processing steps normally used ahead of these finishes are at the option of the processor. Where a finish requires two or more treatments of the same class, the class letter is repeated, each time being followed by the appropriate two-digit numeral.

Designations for specific coatings have been developed only for the anodic coatings. Coatings of the four other classes may be tentatively designated by the letters respectively assigned for them; detailed designations for these four categories may be developed and added to the system later.

The examples that follow show how the designation system for aluminum finishes is used. Each designation is preceded by the letters "AA" to identify it as an Aluminum Association appellation. More detailed information can be found in the Association document titled "Designation Systems for Aluminum Finishes, 1980."

Smooth Specular Finish. A finish can be obtained by polishing aluminum with an aluminum oxide compound according to the following schedule. Begin with grits coarser than 320; follow with 320-grit and a wheel speed of 30 m/s (6000 ft/min); complete polishing by buffing with tripoli-based buffing compound at 35 to 41 m/s (7000 to 8000 ft/min). The designation for this finish is AA-M21 (Table 25).

Architectural Building Panel. A matte-anodized finish for a building, such as that produced by giving aluminum a matte finish, then chemical cleaning followed by architectural class II natural anodizing, would be designated as AA-M32C12A31:

AA	Aluminum Association
M32	Mechanical finish, directional textured, medium satin appearance
C12	Chemical treatment, inhibited alkaline cleaning
A31	Anodic coating, architectural class II (10 to 18 μm, or 0.4 to 0.7 mil thick), clear (natural)

Architectural Aluminum with Anodized Integral Color. An anodized panel with an integral color for architectural application would be designated as AA-M10C22A42:

AA	Aluminum Association
M10	Unspecified as-fabricated finish
C22	Chemically etched medium matte finish
A42	Anodic coating, architectural class I (18 μm, or 0.7 mil or thicker), integral color

Chromium-Plated Aluminum Panel. T h e finish for a chromium-plated aluminum panel that is first given a highly specular mechanical finish, then a nonetch chemical cleaning, followed by a thin anodic coating produced in phosphoric acid, and finally direct chromium plating, would be designated as AA-M21C12A1XE1X:

AA	Aluminum Association
M21	Mechanical finish, polished, smooth specular (see smooth specular finish, (above)
C12	Inhibited alkaline cleaned
A1X	Specify exact anodizing process
E1X	Specify exact chromium plating method

ACKNOWLEDGMENT

SELECTED REFERENCES

- J.R. Davis, Ed., *ASM Specialty Handbook: Aluminum and Aluminum Alloys*, ASM International, 1993
- J.E. Hatch, Ed., *Aluminum: Properties and Physical Metallurgy*, ASM, 1984
- G.H. Kissen, Anodic Coatings on Aluminum, *The Properties of Electrodeposited Metals and Alloys: A Handbook*, 2nd ed., W.H. Safranek, Ed., American Electroplaters and Surface Finishers Society, 1986, p 29-34
- G.H. Kissen, Ed., *Finishing of Aluminum*, Reinhold, 1963
- N.V. Parthasaradhy, Electroplating on Aluminum and Its Alloys, *Practical Electroplating Handbook*, Prentice Hall, 1989, p 138-147
- S. Wernick, R. Pinner, and P.B. Sheasby, *The Surface Treatment and Finishing of Aluminum and Its Alloys*, Vol 1 and 2, Finishing Publications Ltd., 1987