ASM Handbook, Volume 7: Powder Metal Technologies and Applications
P.W. Lee, Y. Trudel, R. Iacocca, R.M. German, B.L. Ferguson, W.B. Eisen, K. Moyer,
D. Madan, and H. Sanderow, editors, p 834-839
DOI: 10.1361/asmhba0001576

Conventional Aluminum Powder Metallurgy Alloys

ALUMINUM P/M PARTS are used in an increasing number of applications. The business machine market currently uses the greatest variety of aluminum P/M parts. Other markets that indicate growth potential include automotive components, aerospace components, power tools, appliances, and structural parts. Due to their mechanical and physical properties, aluminum P/M alloys provide engineers with flexibility in material selection and design. A variety of pressed and sintered aluminum P/M parts are shown in Fig. 1.

Conventionally pressed and sintered aluminum powder metal parts have been commercially available for many years. Sintered aluminum P/M parts are competitive with many aluminum castings, extrusions, and screw machine products that require expensive and time-consuming finishing operations. In addition, sintered aluminum P/M parts compete with other metal powder parts in applications where some of the attractive physical and mechanical properties of aluminum can be used. The following combination of properties make aluminum attractive for P/M parts:

- Light weight
- Corrosion resistance
- High strength
- Good ductility
- Nonmagnetic properties
- Conductivity
- Machinability
- Variety of finishes

In addition, P/M technology can be used to refine microstructures compared with those made by conventional ingot metallurgy (I/M), which often results in improved mechanical and corrosion properties. Microstructural refinement by P/M is made possible by two broad high-strength P/M technologies—rapid solidification (RS) and mechanical attrition (mechanical alloying/dispersion strengthening). The advantages of P/M stem from the ability of small particles to be processed. This enables:

- The realization of RS rates
- The uniform introduction of strengthening features, that is, barriers to dislocation motion, from the powder surfaces

The powder processes of rapid solidification and mechanical attrition lead to microstructural grain refinement and, in general, better mechanical properties of the alloy. In addition, RS can extend the alloying limits in aluminum by enhancing super-saturation and thereby enabling greater precipitation hardening without the harmful segregation effects from overalloyed I/M alloys. Moreover, elements that are essentially insoluble in the solid state, but have significant solubility in liquid aluminum, can be uniformly dispersed in the powder particles during RS. This can lead to the formation of novel strengthening phases that are not possible by conventional I/M, while also suppressing the formation of equilibrium phases that are deleterious to toughness and corrosion resistance. These topics and the development of dispersion strengthened aluminum-base composites by P/M methods are discussed in the article "Advanced Aluminum Powder Metallurgy Alloys and Composites" in this Volume.

This article focuses on more conventional aluminum P/M alloys and process methods. There are several steps in aluminum P/M technology that can be combined in various ways, but they will be conveniently described in three general steps:

- Powder production
- Powder processing (optional)
- Degassing and consolidation

Powder can be made by various RS processes including atomization, splat quenching to form particulates, and melt spinning to form ribbon. Alternatively, powder can be made by non-RS processes such as by chemical reactions including precipitation, or by machining bulk material. Powder-processing operations are optional and include mechanical attrition (for example, ball milling) to modify powder shape and size or to

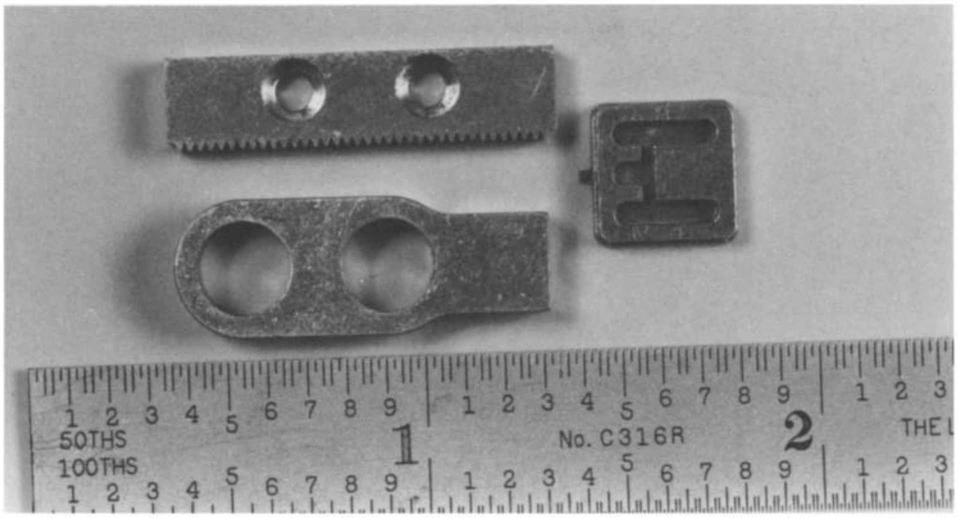

Fig. 1 Typical pressed and sintered aluminum P/M parts made from alloy 601AB. Top: gear rack used on a disc drive. Bottom: link flexure used on a print tip for a typewriter. Right: header/cavity block used on a high-voltage vacuum capacitor. Courtesy of D. Burton, Perry Tool & Research Company

introduce strengthening features, or comminution such as that used to cut melt-spun ribbon into powder flakes for subsequent handling.

Aluminum has a high affinity for moisture, and aluminum powders readily adsorb water. The elevated temperatures generally required to consolidate aluminum powder cause the water of hydration to react and form hydrogen, which can result in porosity in the final product, or under confined conditions, can cause an explosion. Consequently, aluminum powder must be degassed prior to consolidation. This is often performed immediately prior to consolidation at essentially the same temperature as that for consolidation to reduce fabrication costs. Consolidation may involve forming a billet that can be subsequently rolled, extruded, or forged conventionally, or the powder may be consolidated during hot working directly to finished-product form.

Powder Production

Atomization is the most widely used process to produce aluminum powder. Aluminum is melted, alloyed, and sprayed through a nozzle to form a stream of very fine particles that are rapidly cooled—most often by an expanding gas. Atomization of aluminum is discussed in more detail in the article "Production of Aluminum Powders" in this Volume.

Splat cooling is the process that enables cooling rates even greater than those obtained in atomization. Aluminum is melted and alloyed, and liquid droplets are sprayed or dropped against a chilled surface of high thermal conductivity—for example, a copper wheel that is water cooled internally. The resultant splat particulate is removed from the rotating wheel to allow subsequent droplets to contact the bare, chilled surface. Cooling rates of 10^5 K/s are typical, with rates up to 10^9 K/s reported.

Melt-spinning techniques are somewhat similar to splat cooling. The molten aluminum alloy rapidly impinges a cooled, rotating wheel, producing rapidly solidified product that is often in ribbon form. The leading commercial melt-spinning process is the planar flow casting (PFC) process (Ref 1). The liquid stream contacts a rotating wheel at a carefully controlled distance to form a thin, rapidly solidified ribbon and also to reduce oxidation. The ribbon could be used for specialty applications in its PFC form but is most often comminuted into flake powder for subsequent degassing and consolidation.

Press and Sintered Aluminum Alloys

Commercially available aluminum powder alloy compositions (Table 1) consist of blends of atomized aluminum powders mixed with powders of various alloying elements such as zinc, copper, magnesium, and silicon. Press and sintered aluminum alloys are based on elemental blends. Prealloyed aluminum powders cannot be

Table 1 Compositions of typical aluminum P/M alloy powders

Grade	Composition, %				
	Cu	Mg	Si	Al	Lubricant
601AB	0.25	1.0	0.6	bal	1.5
201AB	4.4	0.5	0.8	bal	1.5
602AB	...	0.6	0.4	bal	1.5
202AB	4.0	...	...	bal	1.5
MD-22	2.0	1.0	0.3	bal	1.5
MD-24	4.4	0.5	0.9	bal	1.5
MD-69	0.25	1.0	0.6	bal	1.5
MD-76	1.6	2.5	...	bal	1.5

processed by conventional P/M press and sinter operations. The non-reducible aluminum oxide coating hinders the development of strong interparticle bonds.

The most common heat-treatable grades are comparable to the 2*xxx* and 6*xxx* series wrought aluminum alloys. Alloys 201AB and MD-24 are most similar to wrought alloy 2014. They develop high strength and offer moderate corrosion resistance. Alloys 601AB and MD-69 are similar to wrought alloy 6061. These alloys offer high strength, good ductility, corrosion resistance, and can be specified for anodized parts. Alloy 601AC is the same as 601AB, but does not contain an admixed lubricant. It is used for isostatic and die-wall-lubricated compaction. When high conductivity is required, alloy 602AB often is used. Conductivity of 602AB ranges from 24×10^6 to 28×10^6 S/m (42.0 to 49% IACS), depending on the type of heat treatment selected.

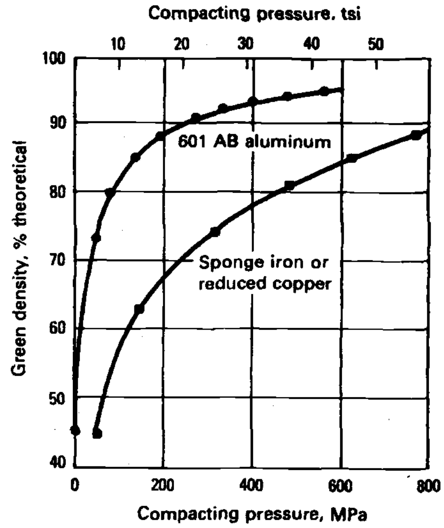

Fig. 2 Relationship of green density and compacting pressure

Aluminum P/M Part Processing

Basic design details for aluminum P/M parts involve the same manufacturing operations, equipment, and tooling that are used for iron, copper, and other metal-powder compositions.

Compacting. Aluminum P/M parts are compacted at low pressures and are adaptable to all types of compacting equipment. The pressure density curve, which compares the compacting characteristics of aluminum with other metal powders, indicates that aluminum is simpler to compact. Figure 2 shows the relative difference in compacting characteristics for aluminum and sponge iron or copper.

The lower compacting pressures required for aluminum permit wider use of existing presses. Depending on the press, a larger part often can be made by taking advantage of maximum press force. For example, a part with a 130 cm^2 (20 $in.^2$) surface area and 50 mm (2 in.) depth is formed readily on a 4450 kN (500 ton) press. The same part in iron would require a 5340 kN (600 ton) press. In addition, because aluminum responds better to compacting and moves more readily in the die, more complex shapes having more precise and finer detail can be produced.

Sintering. Aluminum P/M parts can be sintered in a controlled, inert atmosphere or in vacuum. Sintering temperatures are based on alloy composition and generally range from 595 to 625 °C (1100 to 1160 °F). Sintering time varies from 10 to 30 min. Nitrogen, dissociated ammonia, hydrogen, argon, and vacuum have been used for sintering aluminum; however, nitrogen is preferred because it results in high as-sintered mechanical properties (Table 2). It is also economical in bulk quantities, If a protective atmosphere is used, a dew point of –40 °C (–40 °F) or below is recommended. This is equivalent to a moisture content of 120 mL/m^3 (120 ppm) maximum.

Aluminum preforms can be sintered in batch furnaces or continuous radiant tube mesh or cast belt furnaces. Optimum dimensional control is best attained by maintaining furnace temperature at ±2.8 °C (±5 °F). Typical heating cycles for aluminum parts sintered in various furnaces are illustrated in Fig. 3.

Mechanical properties are directly affected by thermal treatment. All compositions respond to solution heat treating, quenching, and aging in the same manner as conventional heat-treatable alloys. More detailed information on sintering of aluminum can be found in the article "Production Sintering Practices" in this Volume.

Repressing. The density of sintered compacts may be increased by repressing. When repressing is performed primarily to improve the dimensional accuracy of a compact, it usually is termed "sizing"; when performed to improve configuration, it is termed "coining." Repressing

Table 2 Typical properties of nitrogen-sintered aluminum P/M alloys

Alloy	Compacting pressure		Green density		Green strength		Sintered density		Temper	Tensile strength(a)		Yield strength(a)		Elongation,	Hardness
	MPa	tsi	%	g/cm³	MPa	psi	%	g/cm³		MPa	ksi	MPa	ksi	%	
601AB	96	7	85	2.29	3.1	450	91.1	2.45	T1	110	16	48	7	6	55-60 HRH
									T4	141	20.5	96	14	5	80-85 HRH
									T6	183	26.5	176	25.5	1	70-75 HRE
	165	12	90	2.42	6.55	950	93.7	2.52	T1	139	20.1	88	12.7	5	60-65 HRH
									T4	172	24.9	114	16.6	5	80-85 HRH
									T6	232	33.6	224	32.5	2	75-80 HRE
	345	25	95	2.55	10.4	1500	96.0	2.58	T1	145	21	94	13.7	6	65-70 HRH
									T4	176	25.6	117	17	6	85-90 HRH
									T6	238	34.5	230	33.4	2	80-85 HRE
602AB	165	12	90	2.42	6.55	950	93.0	2.55	T1	121	17.5	59	8.5	9	55-60 HRH
									T4	121	17.5	62	9	7	65-70 HRH
									T6	179	26	169	24.5	2	55-60 HRE
	345	25	95	2.55	10.4	1500	96.0	2.58	T1	131	19	62	9	9	55-60 HRH
									T4	134	19.5	65	9.5	10	70-75 HRH
									T6	186	27	172	25	3	65-70 HRE
201AB	110	8	85	2.36	4.2	600	91.0	2.53	T1	169	24.5	145	24	2	60-65 HRE
									T4	210	30.5	179	26	3	70-75 HRE
									T6	248	36	248	36	0	80-85 HRE
	180	13	90	2.50	8.3	1200	92.9	2.58	T1	201	29.2	170	24.6	3	70-75 HRE
									T4	245	35.6	205	29.8	3.5	75-80 HRE
									T6	323	46.8	322	46.7	0.5	85-90 HRE
	413	30	95	2.64	13.8	2000	97.0	2.70	T1	209	30.3	181	26.2	3	70-75 HRE
									T4	262	38	214	31	5	80-85 HRE
									T6	332	48.1	327	47.5	2	90-95 HRE
202AB compacts	180	13	90	2.49	5.4	780	92.4	2.56	T1	160	23.2	75	10.9	10	55-60 HRH
									T4	194	28.2	119	17.2	8	70-75 HRH
									T6	227	33	147	21.3	7.3	45-50 HRE
Cold-formed parts (19% strain)	180	13	90	2.49	5.4	780	92.4	2.56	T2	238	33.9	216	31.4	2.3	80 HRE
									T4	236	34.3	148	21.5	8	70 HRE
									T6	274	39.8	173	25.1	8.7	85 HRE
									T8	280	40.6	250	36.2	3	87 HRE

(a) Tensile properties determined using powder metal flat tension bar (MPIF standard 10-63), sintered 15 min at 620 °C (1150 °F) in nitrogen

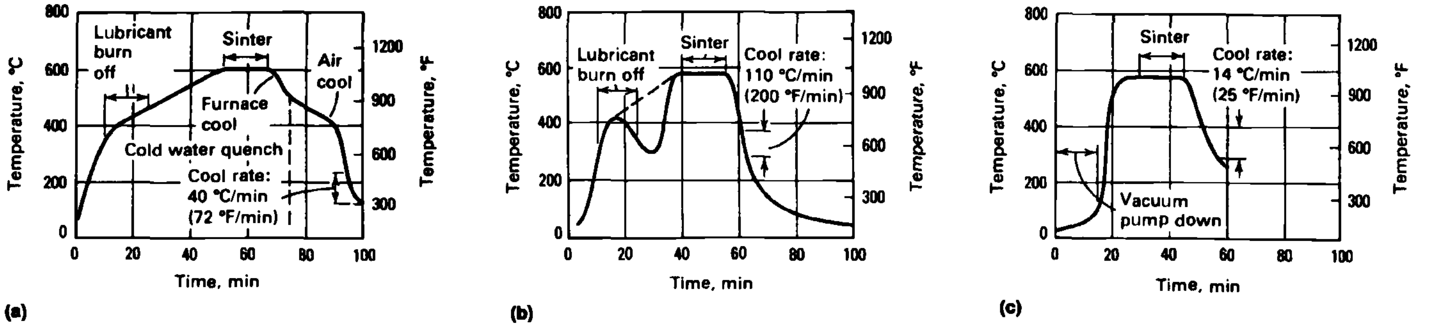

Fig. 3 Typical heating cycles for aluminum P/M parts sintered in (a) a batch furnace. (b) a continuous furnace. (c) a vacuum furnace

may be followed by resintering, which relieves stress due to cold work in repressing and may further consolidate the compact. By pressing and sintering only, parts of >80% theoretical density can be produced. By repressing, with or without resintering, parts of ≥90% theoretical density can be produced. The density attainable is limited by the size and shape of the compact.

Forging of aluminum is a well-established technology. Aluminum also lends itself to the forging of P/M preforms to produce structural parts.

In forging of aluminum preforms, the sintered aluminum part is coated with a graphite lubricant to permit proper metal flow during forging. The part is either hot or cold forged; hot forging at 300 to 450 °C (575 to 850 °F) is recommended for parts requiring critical die fill. Forging pressure usually does not exceed 345 MPa (50 ksi). Forging normally is performed in a confined die so that no flash is produced and only densification and lateral flow result from the forging step. Scrap loss is <10% compared to conventional forging, which approaches 50%. Forged aluminum P/M parts have densities of >99.5% of theoretical density. Strengths are higher than nonforged P/M parts, and in many ways, are similar to conventional forging. Fatigue endurance limit is doubled over that of nonforged P/M parts.

Alloys 601AB, 602AB, 201AB, and 202AB are designed for forgings. Alloy 202AB is especially well suited for cold forging. All of the aluminum powder alloys respond to strain hardening and precipitation hardening, providing a wide range of properties. For example, hot forging of alloy 601 AB-T4 at 425 °C (800 °F) followed by heat treatment gives ultimate tensile strengths of 221 to 262 MPa (32 to 38 ksi), and a yield strength of 138 MPa (20 ksi), with 6 to 16% elongation in 25 mm (1 in.).

Alloy 601AB. Heat treated to the T6 condition, 601AB has tensile properties of:

- UTS, 303 to 345 MPa (44 to 50 ksi)
- Yield strength, 303 to 317 MPa (44 to 46 ksi)
- Elongation, up to 8%

Forming pressure and percentage of reduction during forging influence final properties.

Alloy 201AB. In the T4 condition, alloy 201AB has tensile properties of:

- UTS, 358 to 400 MPa (52 to 58 ksi)

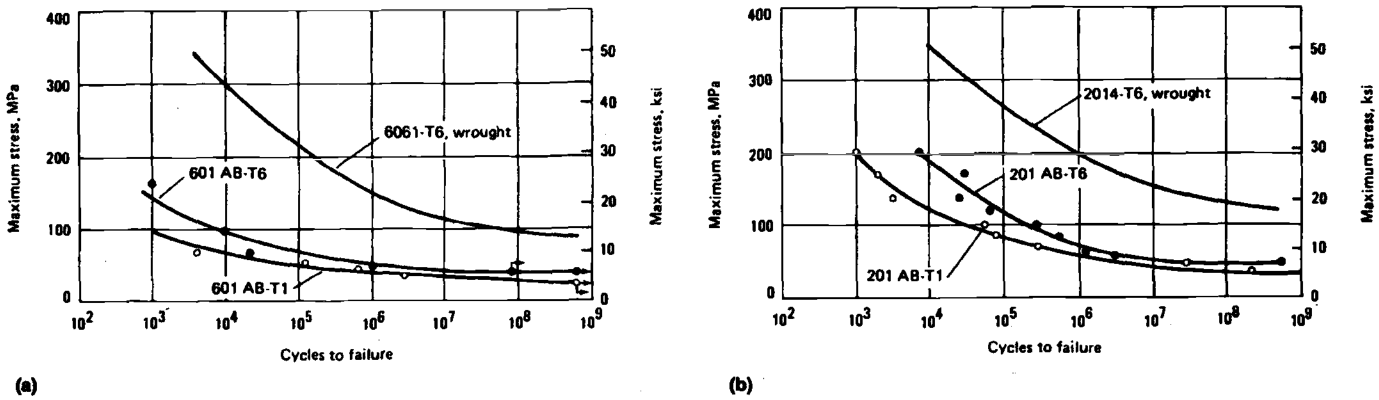

Fig. 4 Fatigue curves for (a) P/M 601AB (b) P/M 201AB

- Yield strength, 255 to 262 MPa (37 to 38 ksi)
- Elongation, 8 to 18%

When heat treated to the T6 condition, the tensile strength of 201AB increases from 393 to 434 MPa (57 to 63 ksi). Yield strength for this condition is 386 to 414 MPa (56 to 60 ksi), and elongation ranges from 0.5 to 8%.

Properties of cold-formed aluminum P/M alloys are increased by a combination of strain-hardened densification and improved interparticle bonding. Alloy 601AB achieves 257 MPa (37.3 ksi) tensile strength and 241 MPa (34.9 ksi) yield strength after forming to 28% upset. Properties for the T4 and T6 conditions do not change notably between 3 and 28% upset. Alloy 602AB has moderate properties with good elongation. Strain hardening (28% upset) results in 221 MPa (32 ksi) tensile and 203 MPa (29.4 ksi) yield strength. The T6 temper parts achieve 255 MPa (37 ksi) tensile strength and 227 MPa (33 ksi) yield strength. Highest cold-formed properties are achieved by 201AB. In the as-formed condition, yield strength increases from 209 MPa (30.3 ksi) for 92.5% density to 281 MPa (40.7 ksi) for 96.8% density.

Alloy 202AB is best suited for cold forming. Treating to the T2 condition, or as-cold formed, increases the yield strength significantly. In the T8 condition, 202AB develops 280 MPa (40.6 ksi) tensile strength and 250 MPa (36.2 ksi) yield strength, with 3% elongation at the 19% upset level.

Properties of Sintered Parts

Mechanical Properties. Sintered aluminum P/M parts can be produced with strength that equals or exceeds that of iron or copper P/M parts. Tensile strengths range from 110 to 345 MPa (16 to 50 ksi), depending on composition, density, sintering practice, heat treatment, and repressing procedures. Table 2 lists typical properties of four nitrogen-sintered P/M alloys. Properties of heat-treated, pressed, and sintered grades are provided in Table 3.

Impact tests are used to provide a measure of toughness of powder metal materials, which are somewhat less ductile than similar wrought compositions. Annealed specimens develop the highest impact strength, whereas fully heat-treated parts have the lowest impact values. Alloy 201AB generally exhibits higher impact resistance than alloy 601AB at the same percent density, and impact strength of 201AB increases with increasing density. A desirable combination of strength and impact resistance is attained in the T4 temper for both alloys. In the T4 temper, 95% density 201AB develops strength and impact properties exceeding those for as-sintered 99Fe-1C alloy, a P/M material frequently employed in applications requiring tensile strengths under 345 MPa (50 ksi).

Fatigue is an important design consideration for P/M parts subject to dynamic stresses. Fatigue strengths of pressed and sintered P/M parts may be expected to be about half those of the wrought alloys of corresponding compositions (see comparisons of two P/M alloys with two wrought alloys in Fig. 4). These fatigue-strength levels are suitable for many applications.

Electrical and Thermal Conductivity. Aluminum has higher electrical and thermal conductivities than most other metals. Table 4 compares the conductivities of sintered aluminum alloys with wrought aluminum, brass, bronze, and iron.

Machinability. Secondary finishing operations such as drilling, milling, turning, or grinding can be performed easily on aluminum P/M parts. Aluminum P/M alloys provide excellent chip characteristics; compared to wrought aluminum alloys, P/M chips are much smaller and are broken more easily with little or no stringer buildup. This results in improved tool service life and higher machinability ratings.

Powder Degassing and Consolidation

The water of hydration that forms on aluminum powder surfaces must be removed to prevent porosity in the consolidated product. Although solid-state degassing has been used to reduce the hydrogen content of aluminum P/M wrought products, it is far easier and more effective to remove the moisture from the powder. Degassing is often performed in conjunction with consolidation, and the most commonly used techniques are described below. The vari-

Table 3 Typical heat-treated properties of nitrogen-sintered aluminum P/M alloys

	Grades			
Heat-treated variables and properties	**MD-22**	**MD-24**	**MD-69**	**MD-76**
Solution treatment				
Temperature, °C (°F)	520 (970)	500 (930)	520 (970)	475 (890)
Time, min	30	60	30	60
Atmosphere	Air	Air	Air	Air
Quench medium	H_2O	H_2O	H_2O	H_2O
Aging				
Temperature, °C (°F)	150 (300)	150 (300)	150 (300)	125 (257)
Time, h	18	18	18	18
Atmosphere	Air	Air	Air	Air
Heat-treated (T6) properties(a)				
Transverse-rupture strength, MPa (ksi)	550 (80)	495 (72)	435 (63)	435 (63)
Yield strength, MPa (ksi)	200 (29)	195 (28)	195 (28)	275 (40)
Tensile strength, MPa (ksi)	260 (38)	240 (35)	205 (30)	310 (45)
Elongation, %	3	3	2	2
Rockwell hardness, HRE	74	72	71	80
Electrical conductivity, %IACS	36	32	39	25

(a) T6, solution heat treated, quenched, and artificially age hardened

Table 4 Electrical and thermal conductivity of sintered aluminum alloys, wrought aluminum, brass, bronze, and iron

Material	Temper	Electrical conductivity(a) at 20 °C (68 °F), %IACS	Thermal conductivity(b) at 20 °C (68 °F), cal/cm·s·°C
601AB	T4	38	0.36
	T6	41	0.38
	T61	44	0.41
201AB	T4	32	0.30
	T6	35	0.32
	T61	38	0.36
602AB	T4	44	0.41
	T6	47	0.44
	T61	49	0.45
6061 wrought aluminum	T4	40	0.37
	T6	43	0.40
Brass (35% Zn)	Hard	27	0.28
	Annealed	27	0.28
Bronze (5% Sn)	Hard	15	0.17
	Annealed	15	0.17
Iron (wrought plate)	Hot rolled	16	0.18

(a) Determined with FM-103 Magnatester. (b) Converted from electrical conductivity values

ous aluminum fabrication schemes are summarized in Fig.5.

Can Vacuum Degassing. This is perhaps the most widely used technique for aluminum degassing because it is relatively non-capital intensive. Powder is encapsulated in a can, usually aluminum alloys 3003 or 6061, as shown schematically in Fig. 6. A spacer is often useful to increase packing and to avoid safety problems when the can is welded shut. It has been found that packing densities are typically 60% of theoretical density when utilizing this method on mechanically alloyed powders. Care must be used to allow a clear path for evolved gases through the spacer to prevent pressure buildup and explosion.

To increase packing density, the powder is often cold isostatically pressed (CIP) in a reusable polymeric container before insertion into the can. Powder densities in the CIPed compact of 75 to 80% theoretical density are preferred because they have increased packing density with respect to loose-packed powder, yet allow sufficient interconnected porosity for gas removal. At packing densities of about 84% and higher, effective degassing is not possible for several atomized aluminum-alloy powders (Ref 2,3). Furthermore, one must control CIP parameters to avoid inhomogeneous load transfer through the powder, which can lead to excessive density in the outer regions of the cylindrical compact and much lower densities in the center. Such CIP parameters often must be developed for a specific powder and compact diameter,

The canned powder is sealed by welding a cap that contains an evacuation tube as shown in Fig. 6. After ensuring that the can contains no leaks, the powder is vacuum degassed while heating to elevated temperatures. The rate in gas evolution as a function of degassing temperature depends on powder size, distribution, and composition.

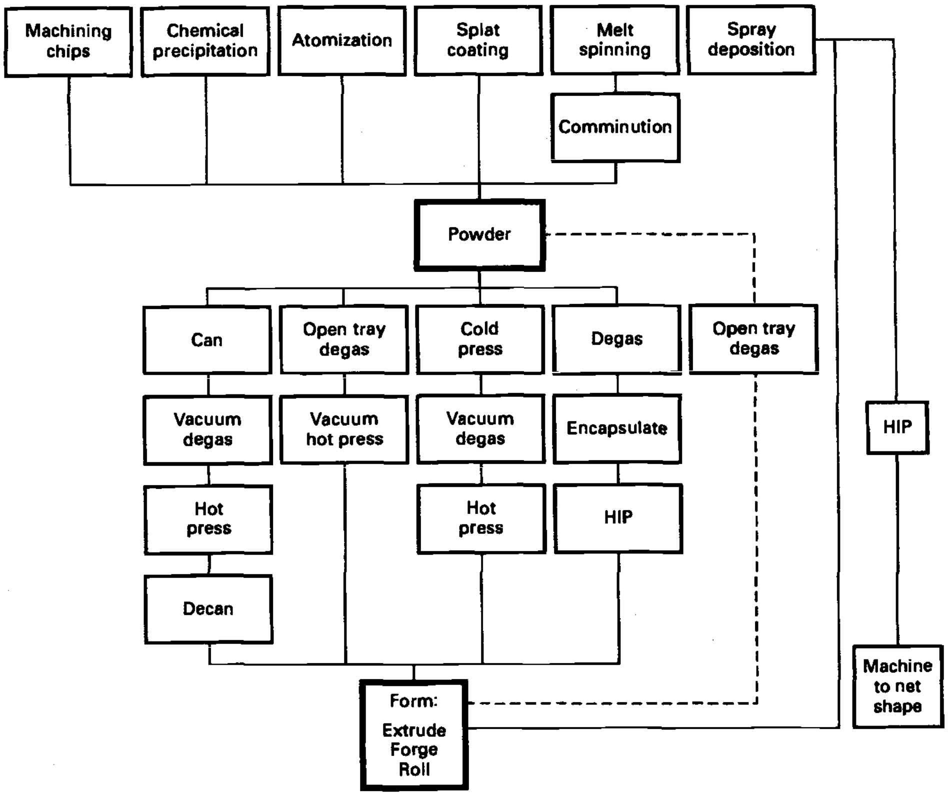

Fig. 5 Aluminum P/M fabrication schemes

The ultimate degassing temperature should be selected based on powder composition, considering tradeoffs between resulting hydrogen content and microstructural coarsening. For example, an RS-P/M precipitation-hardenable alloy that is to be welded would likely be degassed at a relatively high temperature to minimize hydrogen content (hotter is not always better). Coarsening would not significantly decrease the strength of the resulting product because solution treatment and aging would be subsequently performed and provide most of the strengthening. On the other hand, a mechanically attrited P/M alloy that relies on substructural strengthening and will serve in a mechanically fastened application might be degassed at a lower temperature to reduce the annealing out of dislocations and coarsening of substructure.

When a suitable vacuum is achieved (for example, <5 millitorr), the evacuation tube is sealed by crimping. The degassed powder compact can then be immediately consolidated to avoid the costs of additional heating. An extrusion press using a blind die (that is, no orifice) is often a cost-effective means of consolidation.

Dipurative Degassing. Roberts and coworkers at Kaiser Aluminum & Chemical Corporation have developed an improved degassing method called "dipurative" degassing (Ref 4). In this technique, the vacuum-degassed powder, which is often canned, is backfilled with a dipurative gas (that is, one that effectively removes water of hydration) such as extra-dry nitrogen,

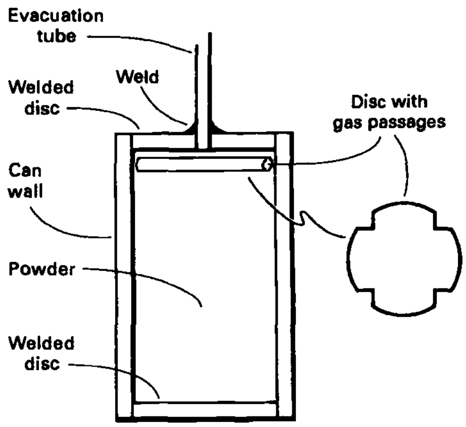

Fig. 6 Degassing can used for aluminum P/M process-

and then re-evacuated. Several backfills and evacuations can be performed resulting in lower hydrogen content. In addition, the degassing can often be performed at lower temperatures to reduce microstructural coarsening.

Vacuum Degassing in a Reusable Chamber. The cost of canning and decanning adversely affects the competitiveness of aluminum P/M alloys. This cost can be alleviated somewhat by using a reusable chamber for vacuum hot pressing. The powder or CIPed compact can be placed in the chamber and vacuum degassed immediately prior to compaction in the same chamber. Alternatively, the powder can be "open tray" degassed, that is, degassed in an unconfined fashion, prior to loading into the chamber. The processing time to achieve degassing in an open tray can be much less than that required in a chamber or can, thereby increasing productivity. Care must be exercised to load the powder into the chamber using suitable protection from ambient air and moisture. The compacted billet can then be formed by conventional hot-working operations.

Direct Powder Forming. One of the most cost-effective means of powder consolidation is direct powder forming. Degassed powder, or powder that has been manufactured with great care to avoid contact with ambient air, can be consolidated directly during the hot-forming operation. Direct powder extrusion and rolling have been successfully demonstrated numerous times over the past two decades (Ref 5, 6). It still remains an attractive means for decreasing the cost of aluminum P/M.

Hot Isostatic Pressing (HIP). In HIP, degassed and encapsulated powder is subjected to hydrostatic pressure in a HIP apparatus. Can vacuum degassing is often used as the precursor step to HIP. Furthermore, net-shape encapsulation of degassed powder can be used to produce certain near net-shape parts. Relatively high HIP pressures (~200 MPa, or 30 ksi) are often preferred. Unfortunately, the oxide layer on the powder particle surfaces is not sufficiently broken up for optimum mechanical properties. A subsequent hot-working operation that introduces shear-stress components is often necessary to improve ductility and toughness.

Rapid Omnidirectional Consolidation. Engineers at Kelsey-Hayes Company have developed a technique to use existing commercial forging equipment to consolidate powders in several alloy systems (Ref 7). Called rapid omnidirectional consolidation (ROC), it is a lower-cost alternative to HIP. In ROC processing, degassed powder is loaded into a thick-walled "fluid die" that is made of a material that plastically flows at the consolidation temperature and pressure, and which enables the transfer of hydrostatic stress to the powder. Early fluid dies were made of mild steels or a Cu-10Ni alloy, with subsequent dies made from ceramics, glass, or composites.

The preheated die that contains powder can be consolidated in <1 s in a forging press, thereby reducing thermal exposure that can coarsen RS microstructures. In addition, productivity is greatly increased by minimizing press time. Depending upon the type of fluid die material being used, the die can be machined off, chemically leached off, melted off, or designed to "pop off" the net-shape component while cooling from the consolidation temperature. For aluminum-alloy powders, unconfined degassing is critical to optimize the cost effectiveness of the ROC process. An electrodynamic degasser was developed for this purpose.

Just as in the case of HIP, the stress state during ROC is largely hydrostatic. Consequently, there may not be sufficient shear stresses to break the oxide layer and disperse the oxides, which can lead to prior powder-particle boundary (PPB) failure. Consequently, a subsequent hot-working step of the ROC billet is often necessary for demanding applications. More detailed information on this technique can be found in Ref 8.

Dynamic Compaction. Various ultrahigh strain-rate consolidation techniques, that is, dynamic compaction, have been developed and utilized for aluminum alloys (Ref 9). In dynamic compaction, a high-velocity projectile impacts the degassed powders that are consolidated by propagation of the resultant shock wave through the powder. The bonding between the powder particles is believed to occur by melting of a very thin layer on the powder surfaces, which is caused by the heat resulting from friction between the powder particles that occurs during impact. The melted region is highly localized and self-quenched by the powder interiors shortly after impact. Thus, dynamic compaction has the advantage of minimizing thermal exposure and microstructural coarsening, while breaking up the PPBs.

ACKNOWLEDGMENT

ASM International gratefully acknowledges J.R. Pickens, Martin Marietta Laboratories. Significant portions of this article were adapted from his article, "High Strength Aluminum P/M Alloys," *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, 1990, p 201–215.

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