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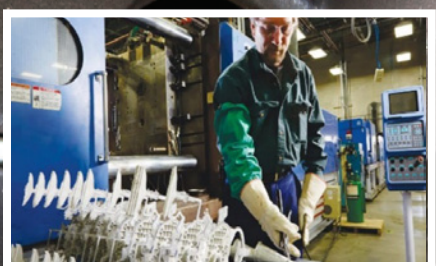
THE MOVE TO MIXED MATERIALS

Unlocking the Right Combination



The Aluminum Powder Metallurgy Option for Lightweighting

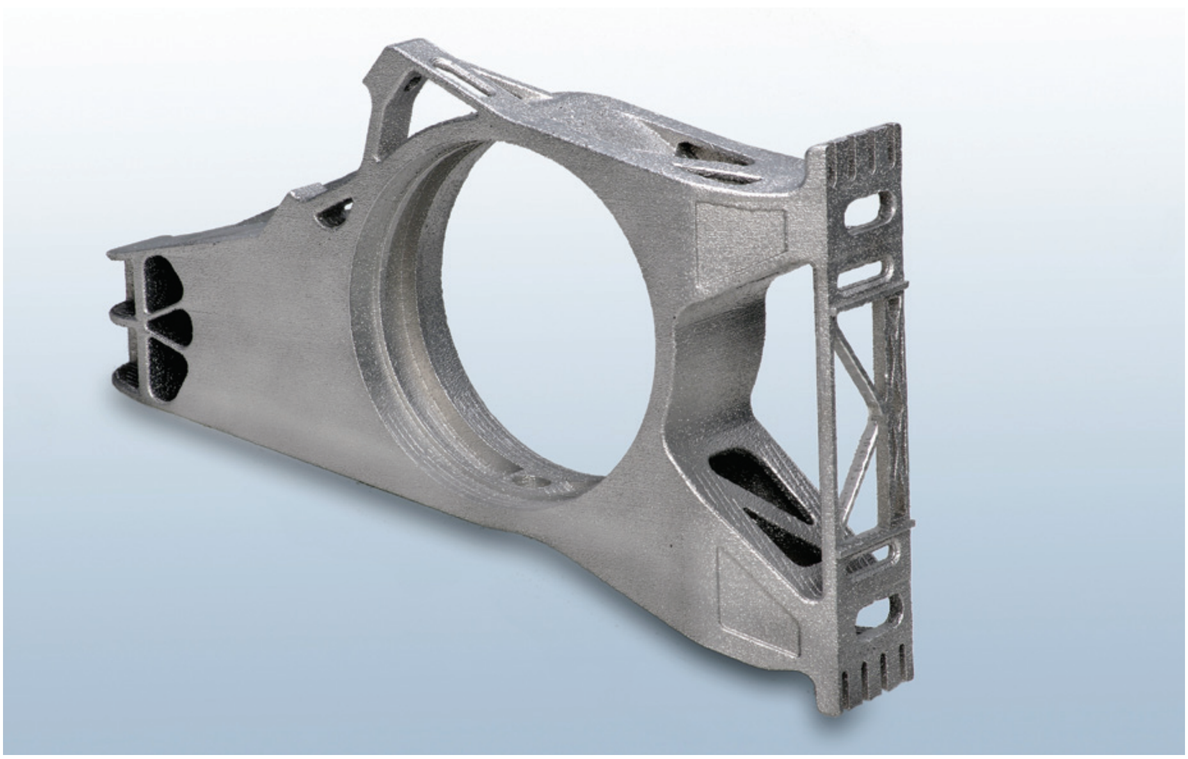
ULTRA-LIGHTWEIGHT DRIVELINE PROJECT

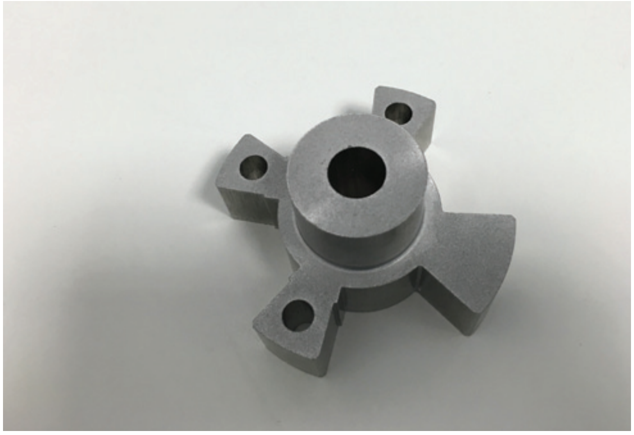
ALUMINUM POWDER METALLURGY

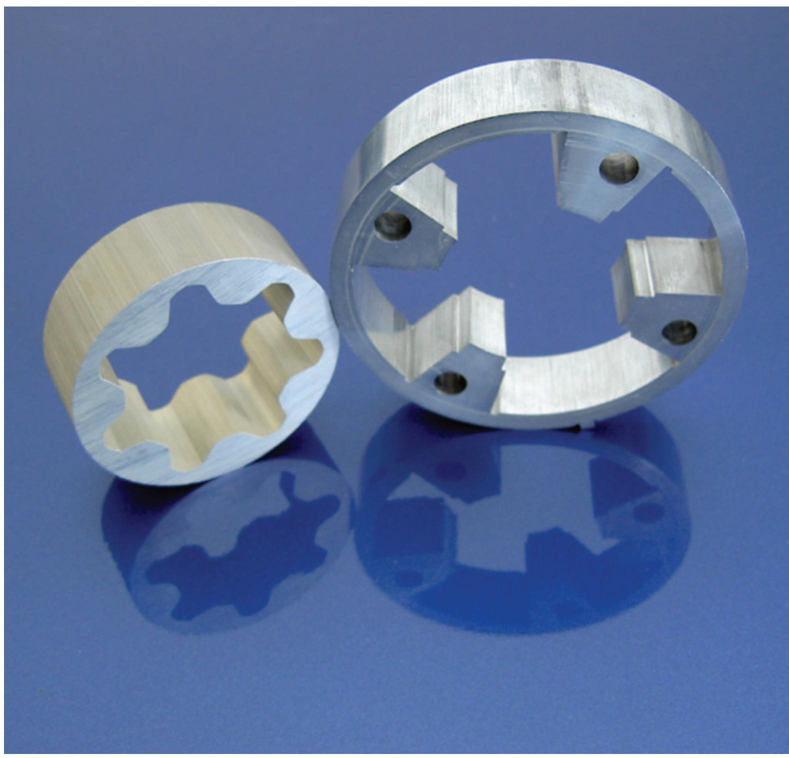
A Versatile & Cost-Effective Option for Lightweighting

By Wayne Daye, SCM Metal Products

Newly developed materials based on aluminum PM technology are viable alternatives for advanced power-train technology and achieving vehicle-weight reduction.







INTRODUCTION

When discussions begin on the selection of metals for lightweighting applications, aluminum and its alloys are among the first options mentioned. The world of wrought- and cast-aluminum materials offers many options for this purpose. One of the less understood aluminum option is aluminum powder metallurgy (PM).

The fundamental weight savings associated with aluminum alloys and the ability to produce precise and consistent net-shaped parts have been two of the driving forces for growth in the aluminum powder metallurgy industry. Aluminum PM offers competition to wrought-aluminum castings and stampings because of its net-shape advantage, especially in high-production volume parts. PM aluminum materials are used to produce complex net and near-net shape parts that require minimal or no machining. Secondary processing (hot pressing, forging, etc.) and heat treatment is used to produce aluminum alloys that compare favorably with conventional wrought alloys. The niche for PM aluminum forgings is in the strength/cost gap between castings and conventional forgings for applications, such as connecting rods, gears and pistons.

The most successful application for PM aluminum is the camshaft bearing cap for overhead camshaft engines. Other key applications include components for shock absorbers, oil-pump rotors and camshaft phasing gears. Additional aluminum PM applications exist in hand tools and recreational equipment. Figure 1 provides an illustration of parts produced by the aluminum PM process.

Four of the most frequently used PM aluminum alloy families are:

- 2000-series (Al-Cu-Si-Mg),
- 4000-series (Al-Si-Cu-Mg),
- 6000-series (Al-Mg-Si-Cu), and
- 5. 7000-series (Al-Zn-Mg-Cu).

Proprietary derivatives of these alloys are used in various applications.

FIGURE [1] / Current applications of sintered PM aluminum (a) a camshaft bearing caps, (b) an end camshaft bearing cap, (c) sintered automotive cam-chaser rotor and a sprocket parts and (d) an aluminum power-tool hub guard

OVERVIEW OF POWDER PRODUCTION

Aluminum powders and aluminum alloys are usually produced by gas atomization. This process uses pressurized gas to disintegrate a molten-metal stream into fine particulates that are subsequently quenched (solidified) by the large volume of cooling gas. This also conveys the powder to the collection vessel for subsequent processing. The cooling rate in an atomization process is significantly more rapid than the cooling rates associated with casting processes—cooling rates can range from 102 to 107 K/s. This rapid solidification not only imparts particle shape and compositional features, but it provides an opportunity to produce unique alloy compositions, as discussed in the section on rapid solidification processing (RSP). Figure 2 illustrates some particle shape options for atomized aluminum powder.

To provide powders for aluminum PM structural parts, powder manufacturers combine selected particulate materials by blending and homogenization. The manufacturer also adds organic lubricants, e.g. amide waxes, to produce a powder that can be compacted (pressed), removed from the compaction tooling and transferred to the sintering process. Quality checks before mixing each component and on each premix before it is released for packaging are performed. Testing methods have been developed (ISO, ASTM, MPIF, DIN, for example) to provide consistent methods for measuring the unique properties of metal powders. A typical aluminum premix lot size can range from 5 kg to 10 tons.

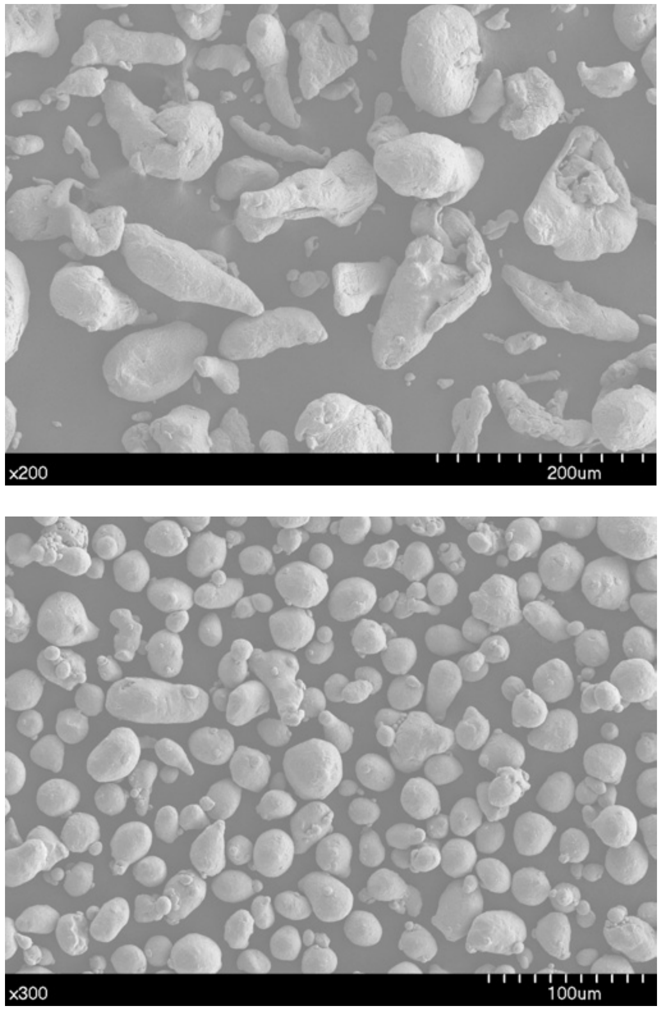


FIGURE [2] / Examples of particle-shape options for aluminum powder

PRESS/SINTER PROCESSING AND PROPERTIES

The initial phase in manufacturing aluminum PM parts involves the consolidation of the powder particles into the physical form of the desired structural part. This is most commonly done by feeding the premixed powder into a coated, hard metal (tool steel or metal carbide) die set and the application of pressure from one or more directions. After the compaction pressure is released, the part is pressed (ejected) from the compaction die. Compacted aluminum PM parts have a shiny, smooth metallic surface due to the superior compressibility of aluminum when compared with iron- or copper-based PM parts. They are typically compacted to 92 percent of theoretical density at pressures of only 250 MPa (18 tsi). The high compressibility of aluminum PM premixes permit the fabrication of larger components using standard powder-pressing equipment. These parts also have sufficient strength (“green strength”) to provide easy transfer to the subsequent sintering process.

The sintering process develops the part’s mechanical and physical properties. Fundamentally, this process involves exposing the part to an elevated temperature (approximately 85 percent of the material’s melting point) for a specified amount of time in a controlled atmosphere. One of

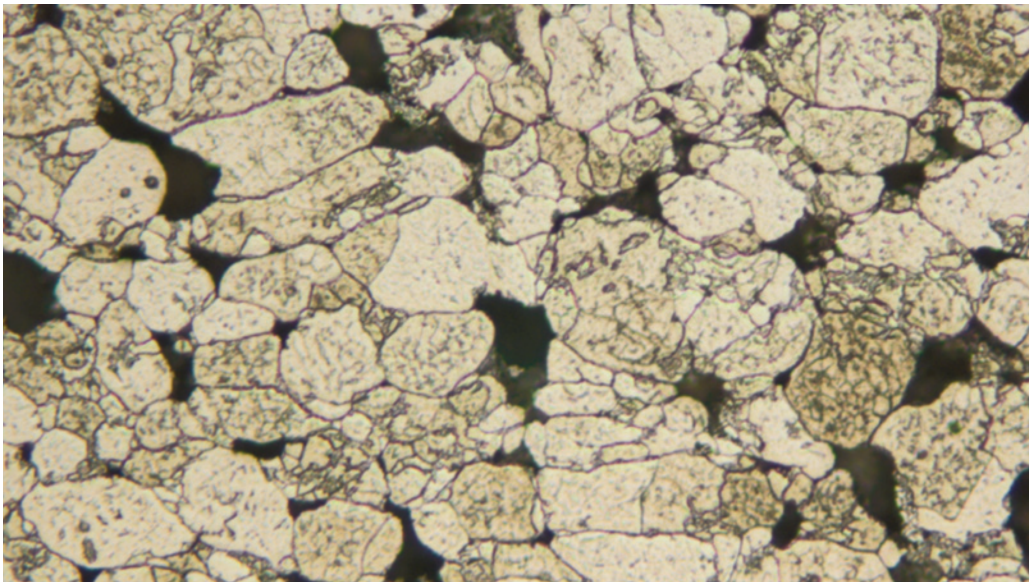


FIGURE [3] / Microstructure of 2000-series aluminum alloy pressed to 2.5 g/cm3 and sintered at 590°C (1095°F) for 20 minutes in dry nitrogen

Just as in the case of cast- and wrought-aluminum alloys, secondary heat treatment can be used to increase the mechanical strength of sintered PM aluminum alloys.

the most commonly used sintering furnace configurations employs a wire-mesh belt to convey the as-compacted parts through a multiple heating-zone furnace. The typical industrial sintering process has three key steps: delubrication (dewaxing), sintering and cooling. In order to produce sintered parts with good mechanical properties, it is necessary to thoroughly remove the lubricant prior to sintering. In aluminum PM parts, this process is typically carried out at 400°C (750°F) for about 20 minutes in dry nitrogen.

Upon completion of the delubrication cycle, the parts are conveyed into the higher-temperature portion of the sintering furnace for completion of the thermal processing. Three of the key variables of the sintering phase are temperature, furnace atmosphere and time-at-temperature. For aluminum PM parts, the sintering temperature typically ranges from 570 to 630°C (1060 to 1170°F). The sintering time-at-temperature depends on the part size, furnace loading (mass of parts/area of the furnace belt) and the heating capacity of the furnace, and typically lasts between 20 to 60 minutes. The parts are then conveyed through the cooling zone, where they cool to near-ambient temperature under the furnace's controlled atmosphere. Figure 3 provides an example of the microstructure of a 2000-series aluminum PM part after sintering.

Just as in the case of cast- and wrought-aluminum alloys, secondary heat treatment can be used to increase the mechanical strength of sintered PM aluminum alloys. The four most commonly used heat-treated conditions are:

- **T1 condition:** Sintered at the recommended temperature and cooled to ambient temperature
- **T2 condition:** Cold worked (sized) and naturally aged at ambient temperature
- **T4 condition:** Annealed in air at 500°C (930°F) for 30 minutes, followed by rapid water/oil quenching and aged hardened at ambient temperature (typically 30 days)
- **T8 condition:** Cold worked (sized), annealed in air at 500°C (930°F) for 30 minutes, followed by rapid water/oil quenching and tempering at 160°C (320°F) for 18 hours.

Table 1 illustrates the impact of heat treatment on the mechanical properties of a 2000-series PM aluminum alloy.

Sizing (calibration) of aluminum PM parts is much more common than other PM materials. The ductility of PM aluminum makes it comparatively easy. The sizing process is usually carried out before precipitation hardening in order to reduce die wear. The T2 condition is the most frequently used heat treatment in the industry.

ALUMINUM PM STANDARDS

Industry standards have been developed to aid designers and engineers in the selection of materials. While there are many industry-specific standards available in the United States, ASTM has been a source for design-related information for a variety of materials. ASTM Standard B595-11 provides the "Standard Specification for Sintered Aluminum Structural Parts" (Ref. 1). This standard covers two materials: a 6000-series PM aluminum (AXX-6061) and a 2000-series grade (ACXX-2014), where "XX" denotes the heat treatment. Key information includes chemical composition, density, mechanical properties, dimensions and tolerances.

The Metal Powder Industries Federation (MPIF) developed materials standards for PM parts to provide design-related properties. The MPIF Standard 35 (Ref. 2) provides such standards for the PM structural parts, and it uses the concept of minimum strength values for the PM materials used in structural applications. The data provided in Standard 35 not only gives the defined values for listed materials, but there is also data on typical mechanical, physical and engineering properties achieved during commercial-manufacturing processes. One will note in this standard that the PM process offers equivalent minimum tensile strength over a wide range of materials. It is seen as an advantage of the process that equivalent strengths can be developed by varying chemical composition, particle configuration, density and/or processing techniques. To define a PM material in both properties and cost effectiveness, it is essential that the part application be reviewed with the PM parts maker.

In the case of PM aluminum, recent work by the MPIF provides standards data for the 2000-series (Al-Cu-Si-Mg) aluminum PM structural parts. This alloy has the grade designation AC-2014. Standards information is provided for two final (sintered) densities—2.50 and 2.60 g/cm3.

HIGH-PERFORMANCE ALUMINUM MATERIALS VIA PM-BASED TECHNOLOGIES

Another key advantage of aluminum PM alloy production is in the manufacture of new alloys and composites with metallurgical structures and chemical compositions that cannot be created using traditional ingot metallurgy. Rapid solidification process (RSP) extends the solubility of alloying elements, particularly transition and rare earth elements, and refines the structure of intermetallic phases. Many of the newer aluminum PM products exploit RSP to produce pre-alloyed PM materials with strength, toughness, fatigue, corrosion resistance and elevated temperature performance not achievable with conventional wrought alloys.

The industry has used RSP for more than 25 years to produce improved aluminum alloys for ambient-temperature service. The most successful alloys have been derived from the 7000-series (AL-Zn-Mg) alloys, where more highly alloyed variants develop transition-metal intermetallic phases to strengthen the alloys. As shown in Table 2, the mechanical properties developed depend on the mill product form and thermomechanical history *(Ref. 3 and 4)*.

TABLE [1] / Mechanical properties of sintered and heat treated 2000-series PM aluminum alloy

Heat Treatment	Tensile Strength (MPa)	Hardness (HB)	Elongation at Fracture, %
T1	190	60	5
T2	230	63	3
T4	260	75	2
T8	310	80	< 1

TABLE [2] / Comparison of the nominal mechanical properties of pressed and sintered 7075 PM aluminum alloy and RSP aluminum alloys

Alloy	Nominal Composition	Heat Treatment	UTS, MPa	Elongation, %
7075	Al-6Zn-2.5Mg-1.8Cu	T1	300	5
7075	Al-6Zn-2.5Mg-1.8Cu	T76	450	2
7090	Al-8Zn-2.5Mg-1Cu-1.5Co	T7	620	9
7091	Al-6.5Zn-2.5Mg-1.5Cu-0.4Co	T7	595	11
CW67	Al-9Zn-2.5Mg-1.5Cu-0.14Zr-0.1Ni	T7X1	614	12

Additive Manufacturing (AM) is one of the most rapidly expanding manufacturing techniques in the industry.

The R&D team at the SCM Metal Products group of companies has been working on new, PM-based aluminum alloys that apply RSP. These alloys use aluminum with the addition of transition metals ("AL-TM"). The alloys are strengthened with non-periodic structures, amorphous and quasi-crystalline phases, which are made possible by RSP. The alloys exhibit a homogenous microstructure with very fine (30 to 250 nanometers) and evenly distributed transition metal-rich nanospheres in the Al matrix. The nanospheres are largely quasi-crystalline and have exceptionally good thermal stability, as illustrated in Figure 4. Development work continues on improvements for the Al-TM aluminum alloys.

ALUMINUM METAL MATRIX COMPOSITES

Conventional and RSP aluminum PM alloys are mixed with nonmetallic powders to produce PM-based metal matrix composites (MMC). These MMC-based components have high strength at elevated temperature, as well as improved stiffness, fatigue, wear and physical property control relative to wrought and cast alloys. Research has led to the development of MMC products that can be processed via conventional pressing and sintering techniques. Table 3 illustrates how a modification to the basic 2000-series PM aluminum with ceramic particulates (Al2O3) can increase the stiffness (Young's modulus) and mechanical strength (UTS), while still maintaining the ductility of the material.

In addition to press and sinter processing, mechanical alloying (MA) can be a key method in the production of aluminum MMC materials. MA is a dry, high-energy milling technique that disperses insoluble oxides and carbides, particulates, whiskers or fibers that stabilize the microstructure and produces a discontinuously reinforced aluminum (DRA) composite. Through deformation processes like pressing, forging, rolling or extrusion and related thermal processing, the PM-based MMC powder can be converted into a form for the production of a structural component.

Aluminum MMCs have been aimed at the aerospace industry, and they have found application in both new aircraft platforms and the retrofit of aging aircraft systems. The relatively high cost and limited commercial applications have resulted in limited usage. Nonetheless, the technology could solve challenging "next generation" material needs, especially in non-aerospace applications. For example, Ishijima et al. (Ref. 6) developed forged PM aluminum-silicon aluminum alloys for connecting rods for general-purpose engine applications, and their work found that the mass of a conventional die-cast rod could be reduced by more than 30 percent via the aluminum MMC route. Takeda and Hayashi *(Ref. 7)* fabricated net-shape compressor parts from Al-AlN and Al-AlN-SiC composites, and the MMC parts were found to have superior wear resistance.

ALUMINUM IN ADDITIVE MANUFACTURING

Additive Manufacturing (AM) is one of the most rapidly expanding manufacturing techniques in the industry. As the name implies, this technology produces three-dimensional (3-D) objects by adding layer upon layer of the material, which can range from plastic to metal to concrete. The common components of AM technology are a computer, 3-D modeling software (Computer-Aided Design or CAD), machine equipment and a constituent material. Through the CAD file, the AM equipment reads the input data and lays down or adds successive layers of the liquid, powder, sheet or other feed material to produce a 3-D object. AM includes many technology subsets like 3-D printing, rapid prototyping (RP), direct digital manufacturing (DDM), layered manufacturing and additive fabrication.

In the case of a metal component, the AM equipment typically involves a metal powder bed and a controlled heating system to fuse the powder particles. The heat system is frequently derived from an electron beam or laser, and the working atmosphere must be controlled to avoid oxidation. There are a number of active development programs on options for the delivery of the metal feed and fusion technology for the AM of metal components.

FIGURE [4] / Comparison of the loss in mechanical strength of the AL-12.4TM, 2618 and 7075 alloys as a function of temperature

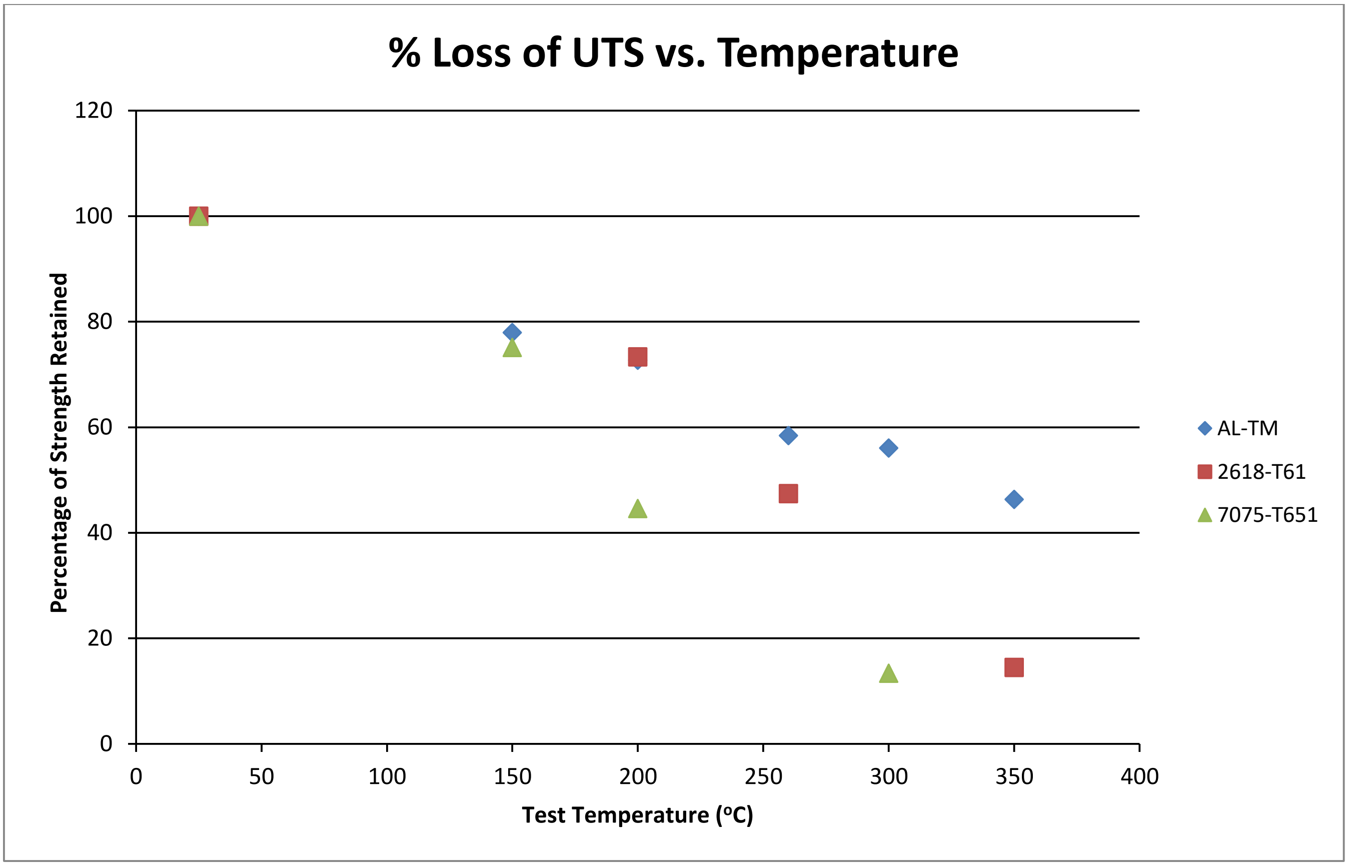


TABLE [3] / Examples of the properties of Al MMC's *(Ref. 5)*

Material	Nominal Composition	Al_2O_3 Addition, %	Heat Treatment	UTS, MPa	Elongation, %	Young's Modulus, GPa
AC-2014	Al-4.5Cu-0.8Si-0.6Mg	0	T1	209	3	60
MMC-A	Al-3Cu-1.5Mg-0.6Sn-0.2Si	5	T1	240	3	70
MMC-B	Al-3Cu-1.5Mg-0.6Sn-0.2Si	10	T1	226	3	76

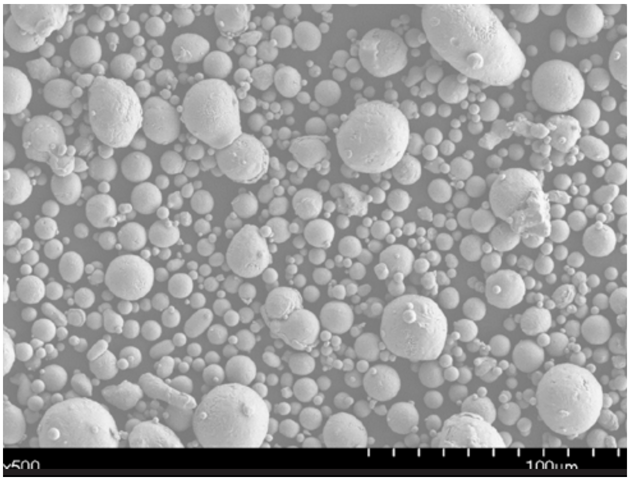


FIGURE [5] / Example of aluminum powder for additive manufacturing

FIGURE [6] / Example of aluminum-additive manufacturing

While materials like stainless steels, nickel alloys and titanium alloys are most often associated with metallic AM parts, aluminum and its alloys are finding more applications. The aluminum-based materials most often used in AM include high purity (>99.7 percent) aluminum, aluminum-silicon alloys, aluminum-silicon-magnesium alloys and aluminum-magnesium-silicon-copper (6061). The powder particle-size distribution, typically < 63 µm, is controlled to meet the customer's requirements, as illustrated in Figure 5. Figure 6 is an example of an aluminum part produced by additive manufacturing.

SUMMARY

The fundamental weight savings associated with aluminum alloys and the ability to produce precise and consistent net-shape parts have been two of the driving forces for the growth in the aluminum powder metallurgy industry. The conventional aluminum PM industry produces millions of cost-effective components each year. Newly developed materials based on aluminum PM technology are viable options for significantly more demanding applications in advanced powertrain technology and to achieve vehicle-weight reduction in automobiles. The end result will be reduced CO_2 emissions and fuel-efficiency improvements. LW

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Wayne Daye has been with the ACuPowder International/ECKA Granules/SCM Metal Products, Inc. group for 20-plus years and has been involved in the PM industry for more than 25 years. As R&D manager, Mr. Daye's work is focused on the development of new PM-based aluminum materials. He holds B.S. and M.S. degrees in materials engineering.