# Aluminium MIM: New advanced powders and feedstocks achieve higher densities

Whist conventional Powder Metallurgy aluminium parts are today processed in high volumes for established end-user industries, aluminium has not yet become established as an accepted material for MIM. There is, however, growing interest in combining the unique properties of aluminium with the ability of MIM to process large volumes of highly complex components. In this paper Jessu Joys, Rhonda Kasler and Clive Ramsey, United States Metal Powders, Inc., report on the testing of a new commercially available MIM feedstock based on a specially developed fine inert gas atomised aluminium powder.

Several studies have been conducted in the field of aluminium Metal Injection Moulding (MIM) in recent years identifying the advantages of MIM aluminium parts. The interest in such parts has always existed due to the unique physical properties of aluminium and the cost advantage achieved in producing a lightweight part with excellent strength. As MIM technology has gained wider acceptance in recent decades, several research papers and a number of patents have been published emphasising the continued quest to commercialise aluminium MIM technology. However the total number of aluminium MIM parts produced remains limited, regardless of the many application opportunities to make high strength aluminium MIM parts.

The paper published by Liu, Kent and Schaffer in 2009 reported an aluminium nitride (AlN) reinforced 6061 alloyed powder composition for Metal Injection Moulding and processing the parts in a sintering furnace surrounded by magnesium blocks to capture the oxygen [1]. Aluminium based powder grades are not new to the Powder Metallurgy (PM) industry and millions of pressed and sintered aluminium automobile parts have been produced for more than two decades, particularly by part producers in US. Just like the difficulties aluminium PM technology experienced in its infancy, aluminium MIM is also going through similar challenges in terms of optimising the raw materials and processing steps to make it an attractive material of choice.

Metal Injection Moulding is a proven technology with the major processing steps consisting of selecting a fine metal powder tailored for MIM and mixing it with a binder to create the feedstock, followed by injection moulding this feedstock to

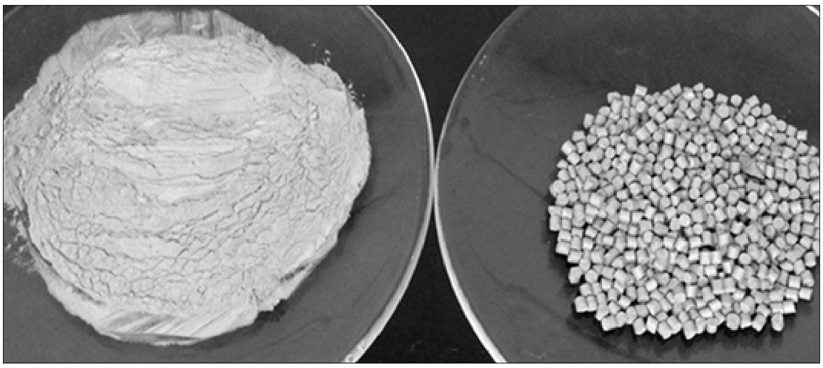

*Fig. 1 Left - MIM 6061 aluminium alloy powder from Ampal, Inc.; Right - aluminium feedstock manufactured by Ryer Inc., using 6061 aluminium powder*

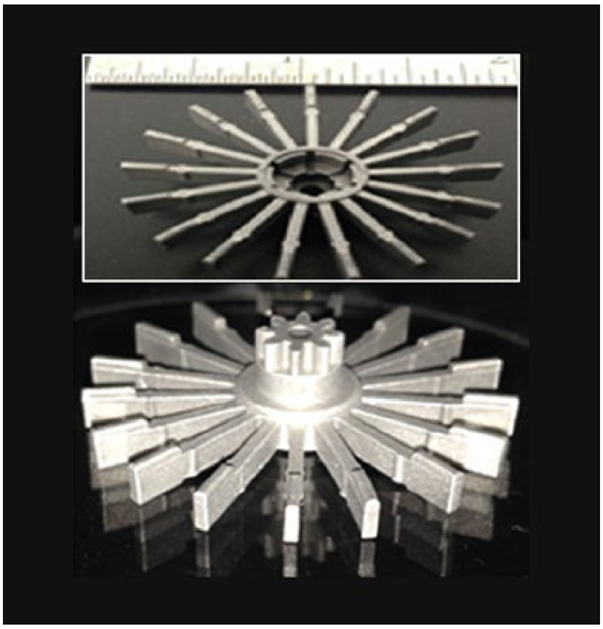

*Fig. 2 Aluminium MIM sample part manufactured by Ryer Inc. using the aluminium 6061 feedstock*

form a part with a three dimensional shape. The binder is then removed by various techniques to produce the finished part with the required geometry via the sintering process. Materials such as stainless steels have gained popularity thanks to these powders being optimised for the MIM process and accompanying standards were defined along with the processing steps. This has not yet happened for aluminium but a field tested feedstock is now available based on a newly developed ultra-fine aluminium alloy powder and a proprietary wax based binder system developed by Ryer, Inc., based in Temecula, California, USA. Fig. 1 shows the ultra-fine aluminium alloy powder MIM 6061 and the wax based feedstock. A sintered aluminium sample part with a 98.6% theoretical density is shown in Fig. 2.

## Advantages of selecting aluminium MIM as a process to produce parts

The list of advantages of aluminium and aluminium injection moulded parts is extensive; however, the only aluminium MIM part that has been repeatedly mentioned in publications is the heat sink. The higher thermal conductivity and greater flexibility in design over extrusion and die-casting are the main reasons to select aluminium MIM technology to make heat sinks [2].

The price of aluminium is also about one third of that of copper based on volume and other common alloyed metal powder grades currently used in the MIM industry. Some of the reasons why aluminium MIM has not gained popularity are its lower strength properties, difficulty in sintering, and until now the lack of availability of feedstock that a part maker can process easily. The size of a typical MIM part is 5 – 100 g and there are several intricate parts that can be manufactured for the electronic and medical industries using aluminium MIM technology. A case study published by Parmatech Corporation [3] discussed replacing a plastic articulation gear that failed due to insufficient strength. The plastic part was temporarily replaced with a machined aluminium part and then permanently replaced with 17-4 stainless grade. There are a lot of great potential opportunities for aluminium MIM to replace parts in this category but it requires part producers to have more experience with processing aluminium MIM parts.

Investment casting and die-casting are two major competitive processes to aluminium MIM. Investment casting is a very competitive process compared to aluminium MIM but the moulds cannot be reused and because of this it is very difficult to make large numbers of parts. High volume complex parts can be produced using die casting but smaller parts with thin walls, along with the difficulties in minimising and/or eliminating porosity, are key disadvantages of this process. Press

| Aluminium MIM Grades | MIM 2024 | MIM 6061 | MIM 7075 |
|---|---|---|---|
| **Chemistry, %** | | | |
| Silicon | 0.5 Max. | 0.4 – 0.8 | 0.4 Max |
| Iron | 0.5 Max. | 0.5 Max. | 0.5 Max |
| Copper | 3.8 – 4.9 | 0.15 – 0.40 | 1.2 – 2.0 |
| Manganese | 0.3 – 0.9 | 0.15 Max. | 0.30 Max. |
| Magnesium | 1.2 – 1.8 | 0.8 – 1.2 | 2.1 – 2.9 |
| Zinc | | | 5.1 – 6.1 |
| Total others | 1.2 Max. | 1.2 Max. | 1.2 Max. |
| $Al_2O_3$ | <0.5 | <0.5 | <0.5 |
| **Particle Size Distribution** | | | |
| d50, µm | 12 – 18 | 12 – 18 | 12 – 18 |
| d90, µm | 34 Max. | 34 Max. | 34 Max. |
| Surface area (BET), m^2/g: | 0.4 Max. | 0.4 Max. | 0.6 Max. |

*Table 1 The chemistry and other measured properties of the selected powder grades*

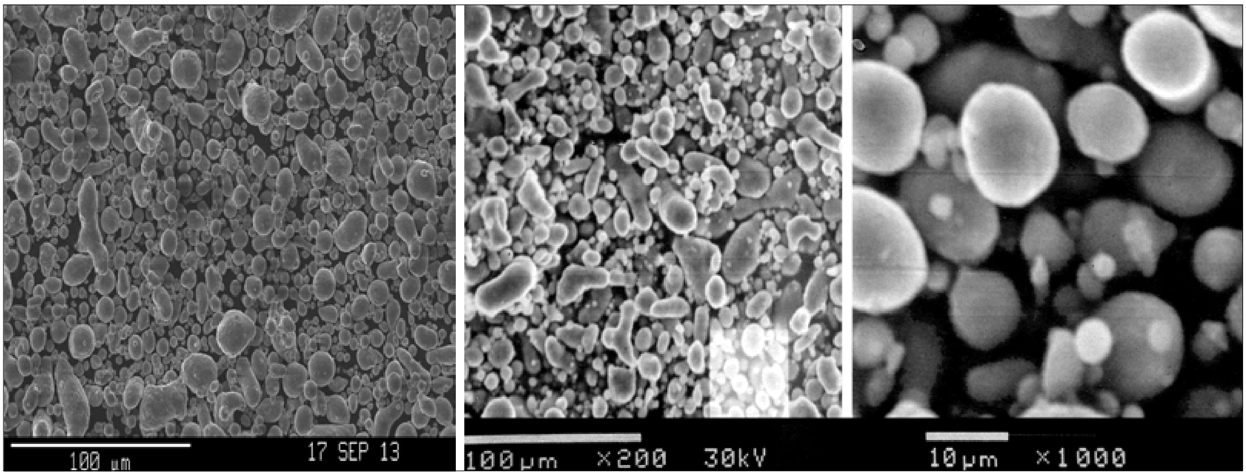


*Fig. 3 SEM images of MIM 6061 (left) and MIM 2024 (centre and right) powder grades*

and sintered Powder Metallurgy is a good option but it is very difficult to make parts with highly complex geometries.

## Surface layers on aluminium powders

The major challenge in the processing of aluminium or aluminium based powder is the surface oxide layer coating with a thickness of approximately 4 nm. This oxide layer needs to be reduced to attain good interparticle contact during sintering. Several methods have been discussed in the past and incorporating a small amount of magnesium in the aluminium was one of the solutions to reduce the oxide coating [4]. This reaction is explained by the equation as:

$3Mg + 4Al_2O_3 = 3MgAl_2O_4 + 2Al$.

Some hydrocarbons and hydroxides can be present on the surface in which the hydroxide can be absorbed from the atmosphere with high moisture content and humidity. One of the most popular methods of making aluminium powder is via the atomisation process and the surface oxide coating will be there regardless of the type of atomisation, whether it is air or inert gas atomisation. The surface oxide coating depends on the type of gas that is used and air atomised powder will have a thicker oxide coating compared to inert gas atomised powder.

## Powder selection

In order to develop specialty grades for aluminium MIM a thorough study was done focusing on the morphology, particle size distribution and chemical composition of the popular wrought alloyed aluminium grades widely known as 2024, 6061 and 7075 alloys. The 2024 alloy has good mechanical properties at elevated temperatures and better resistance to crack propagation. The 6061 alloy is one of the most popular wrought alloyed grades with known properties such as good elongation, extrudability, weldability, machinability, thermal conductivity, electrical conductivity and anti-corrosion properties. The 7075 alloy has excellent mechanical properties via heat treatment and has good corrosion resistance.

All the powder grades evaluated were inert gas atomised and the selected particle shape was spheroidal, as shown in Fig. 3. Particle size distribution is an important factor and the recent trend in the MIM industry is to use finer powder grades with an average particle size of 15 µm or below. Available finer alloyed powder grades with an average particle size (d50) of 10 µm to 20 µm have been reviewed and powder grades with an average particle size of 15 µm were selected as the best option. As the aluminium powder size decreases, the specific surface area increases and the oxide and oxygen content increases. In all three powder grades the aluminium oxide content was kept below 0.5% to improve sintering. The three different grades of powders were specially formulated to aid the sintering process but, as with any process, some parameters may require adjustment.

*'After reviewing the safety concerns in handling fine aluminium powder a commercially available feedstock may be the preferred choice for part makers'*

The chemistry and other measured properties of these powder grades are shown in Table 1. The "Total others" percentage in Table 1 contains proprietary range of other elements. In the MIM industry it is common for part manufacturers to blend their own in-house proprietary feedstock. After reviewing the safety concerns in handling fine aluminium powder, however, a commercially available feedstock may be the

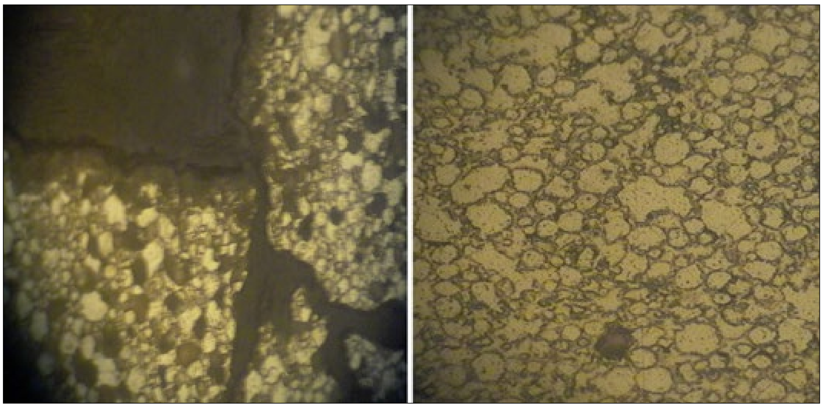

*Fig 4. Metallographic images of parts sintered at 630°C and 640°C-650°C*

preferred choice for part makers. Several companies are evaluating the new aluminium feedstock and we can expect several aluminium MIM parts in the near future.

## Processing of MIM 6061 aluminium alloyed powder

There are several types of binders available on the market today, including water, wax and polymer based binders. A set of parts was prepared using the water based binder but the mechanical properties of the sintered parts were much lower than expected and the microstructural analysis identified poor sintering as the cause. The next binder chosen was a wax based binder and Fig. 1 (Ryer Inc.) shows the commercially prepared feedstock. These proprietary binders can be debound by solvent, Supercritical Fluid Extraction (SFE) or thermal debinding [5]. In the thermal debinding process the binder vaporises and it is also considered as a relatively easy debinding technique.

It has been shown in a study of the liquid phase sintering of aluminium alloys that a nitrogen atmosphere is essential and a dew point of -60°C or better is recommended [6]. The demonstration parts were sintered in a MIM furnace with a 100% nitrogen atmosphere and a dew point of -55°C. In aluminium PM, sintering conditions are closely monitored and optimised as the part goes through a growth phase first before shrinking and stabilising as it spends a fixed amount of time at the correct sintering temperature [4]. Binder removal in aluminium Powder Metallurgy involves the removal of ethylene bistearamide (EBS) or stearates at a lower temperature of 430°C – 510°C under nitrogen atmosphere before sintering. The removal of binders and sintering of aluminium MIM parts is similar to this but the sintering process is much longer and the time it takes to process the parts will be about 8 – 10 hours. The primary binder in this aluminium feedstock burns out in the range of 250 to 300°C and the secondary binder will burn-out in the range of 450°C to 500°C.

A set of experimental sample parts was prepared by Ryer Inc. using a feedstock with a green density of 2.0 g/cm$^3$. The solvent debinding method was chosen to remove the binder. This first set of brown parts were then sintered at 630°C and the microstructural analysis showed poor sintering with a large number of pores and some cracks. The weight of the sample part was about 20 g with an overall outer diameter of about 3.8 cm. The parts were sintered on alumina plates as graphite plates are not recommended since the parts may react with the material [7]. Several trials were done at different temperatures and the processing conditions were optimised to get good sintered properties.

In the next stage of the study a set of tensile bars was moulded, solvent debound and sintered in a furnace with the temperature ranging from 250°C to 650°C. The sintering temperature range was 640°C to 650°C and the overall processing time was around 8 hours in which the parts spent about 1-2 hours at the sintering temperature. This sintering temperature range is very close to the melting point of 6061 alloy (652°C) and can cause melting of parts if

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| | MIM 6061 | MIM 6061 | 6061 (Wrought) | 6061 (Wrought) |
|---|---|---|---|---|
| Heat treatment | As sintered | T6 | T4 | T6 |
| Temperature °C | 640 – 650 | 510 & 177 | | |
| Quenching media | Water | Water | | |
| Ultimate Tensile Strength, MPa | 190 – 200 | 290 – 300 | 207 – 241 | 290 – 310 |
| Density, g/cm$^3$ | 2.66 | | | |

*Table 2 Comparison of tensile properties of MIM 6061 and the wrought alloy 6061*

the temperature is not carefully controlled. Fig. 2 shows a sample part sintered at the optimised sintering conditions using the wax based feedstock with aluminium powder grade MIM 6061.

The sintered density of the test bars was 2.66g/cm$^3$, which is about 98.6% of theoretical density. The tensile properties were tested and the average value of ultimate tensile strength (UTS) was around 200 MPa and the Rockwell hardness value was around 93 (B Scale). Fig. 4 shows the sectional microstructure of the part sintered at 630°C and the part sintered at the optimised temperature range of 640°C to 650°C. The parts sintered at optimised conditions show less porosity and good sintering (Fig. 4). The tensile bars were heat treated (T6) at 510°C for 30 minutes and water quenched to ambient temperature before being solution treated for 185°C for 8 hours. The comparison of tensile properties of MIM 6061 and the wrought alloy 6061 properties is summarised in Table 2.

## Conclusion

This study demonstrates that the successful combination of optimised aluminium alloy powders and the wax based feedstock based on a proprietary binder can overcome the difficulties in the aluminium MIM process.

- The sintered density of the Metal Injection Moulded 6061 aluminium alloy sample parts was very close to the theoretical density.
- The "as sintered" ultimate tensile strength (UTS) value of the MIM 6061 was very close to wrought alloy 6061-T4 value.
- The 6061-T6 heat treated UTS value was also close to the wrought alloy 6061-T6 value.

Several MIM part producers around the world are evaluating the new aluminium alloy powders.

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