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Characterisation of recycled aluminium swarf into fine powder for MIM applications via ball milling

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ABSTRACT

Abstract. Practically, aluminium swarf (chips) collected from an automotive production line is less likely to have any contaminants once the lubricants are removed. In theory, metals do not degrade in value and can be used infinitely. Nowadays, industrial waste management is one of the factors of an enormous concern as the environment is showing prominent signs of ruin, decay, pollution and exhaustion. Thus, recycling or reusing metals in a much energy efficient means aligns with helping to save the environment from rapid collapsion by paddling backwards in excessive energy and resource exhaustion. In powder metallurgy, a branch of manufacturing known as metal injection moulding (MIM) utilises powdered metals to produce high quality parts with zero waste productions. Hence, this study aims produce usable fine powders (50 µm >) from aluminium metal swarf using ball mills which is suitable for MIM applications. Overall, the smallest powder particle size (< 45 µm) of the pulverised aluminium swarf collected shows that 90% are smaller than 61.645 µm in diameter and 50% are smaller than 34.829 µm in diameter after 2 (two) operating cycles of ball milling. The particle shape came out to be irregular but far smoother and bulkier than of a previously flaky texture. Besides that, the purity of the pulverised aluminium swarf is exceptionally comparable to a commercially pure aluminium powder at 91.4wt%. The remaining weight percentage belongs to traces of silicone (Si) that may have been present during swarf (chip) formation from abrasive cutters during production or from cleaning media of the ball mill apparatus. It is found that the key to fine aluminium powder production via ball mill is the size of the grinding media; the smaller the diameter, the smaller the powder particle size produced. Equally important is the milling time, which is kept at 3 minutes and 27 minutes of pause time for adequate jar and grinding media cooling; which reduces the tendency of particle agglomerations.

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Introduction

Waste management is a global and crucial concern that needs to be addressed now with the exponential growth of the industry caused by the parallel increase in consumer demands. Considering that, Malaysia is currently working on engaging with the United Nations Environmental Program (UNEP), production process waste management included. Metal swarf is a by-product of various machining processes within a production line such as grinding, milling, boring, etc. that is basically shavings of raw materials, in this case metals, which are considered as non-functioning outputs [1]. Depending on the country or factory protocols, tonnes and tonnes of metal swarf produced daily are either reused into ingots (raw material) or compacted into fuel burners (briquettes) [2], [3]. As ingots, they do not possess their prior purities due to cross-contamination during waste transfer.

While as briquettes, more of the lubricants are prominently salvaged and recycled but the briquettes tend to be used to fuel furnaces for heating at extremely elevated temperatures. However, making ingots or briquette burning is continuing to exhaust a lot of resource from the earth which is far from sustaining them and adds to atmospheric pollution and health deterioration of all living beings on the planet. These metal swarf need to be put to reuse through better means.

Figure 2: Aluminium metal swarf [9]

Figure 1: Aluminium Briquettes [10]

In this study, we focus on pulverising aluminium swarf (Figure 1) into fine powders (50 µm >) to be used in Metal Injection Moulding (MIM). MIM is a method of mass-producing complex, tiny (about 5 cm > max dimension), high performance metal parts with maximized dimension tolerance and high quality. Looking at Figure 3, some four (4) major steps in MIM are depicted which includes the mixing of powders and binding agents to produce feedstock, injection of said feedstock into a mould cavity for shape definition, removal of binding agent(s) through methods such as liquid or solvent leeching, evaporation and/or heating. Lastly, the remaining component of the feedstock (metal powder) that had retained the shape according to the mould cavity would be slightly melted to join its particles to one another to create a network of powder particulates, inducing shrinkage (optimally 20%>) and elevate its density in a controlled environment; where all residues of binding agent(s) are removed. Post sintering, almost no further finishing is needed unless it serves the function [4]–[6].

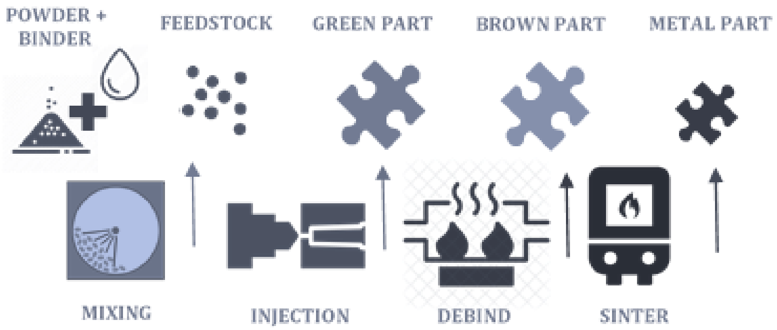

Figure 3: Major sequence of MIM

In conjunction, there are two (2) crucial factors affecting the outcome of the finished part which are the binding agent and metal powder attributes. The optimum powder attributes for the finest outcome should be of 25 µm of average particle size; the smaller the better. Also, having the powder particles in spherical shapes and smooth surfaces are preferred to encourage feasible flow during the injection process. A dendritic or flaky morphology would induce interlocking of powder particles and clogging of feedstock flow during injection. A continuous flow of feedstock is highly desired in MIM to fully fill-in the mould cavity [4], [7]. On another note, some of the commercially produced metal powders are via gas atomisation which requires a significant amount of gas and energy to be used.

However, milling ductile materials such aluminium has never been recommended. This is due to its high tendency to absorb accumulated heat to only liquify and flatten out the particles shape rendered far from desired. This caused some issues such as agglomeration of aluminium to the milling container and media, and increased particle size; defeating the purpose of milling. A way to evade such issues include milling with processing control agents (PCA) and inert gas purging. The PCA helps to prevent from agglomerations to the milling apparatus and the inert gas helps to keep the temperature inside of the milling jar during operation at a minimum. A common practice among researches to avoid agglomeration is adding stearic acid as a PCA; but ends up contributing to carbon accumulation in the process.

Previously, Ramezani and Neitzert (2012) [8] wrote about mechanical alloying a.k.a. ball milling aluminium composite into powders using a large capacity (500 ml) stainless steel jar which successfully achieved 8.9 µm to 12 µm of average powder particle size distribution with methanol as PCA and argon gas purging. In their work, the aluminium powder attributes obtained were granular and almost ideal for injection and sintering. However, although it is not mentioned, it is possible that there might be a noticeable iron (Fe) contamination from the stainless-steel jar and grinding media.

What is being done here is the utilisation of a 250 ml ball mill jar (Fritsch P-6 Planetary Monomill) apparatus to produce fine aluminium powders from aluminium swarf only through high energy impact between grinding media and the walls of its container; without the aid of any PCA or inert gas purging. A Zirconia (ZrO_2) based grinding media and container is used to avoid Fe contaminants into the non-ferrous metal powder. The pulverised aluminium swarf is then sieved using a test sieve with a 600 mesh (0.025 mm) screen strapped on a Vibratory Sieve Shaker for the separation and collection of particles less than 25 µm. The powders produced would not need further processing; meaning it can be used to make feedstock without the removal of remaining PCA.

Methodology

The aluminium swarf collected are from a mass production (automotive) line where they are less likely to be contaminated with other elements i.e. other metal burs, workshop debris, dust, and woodchips. The swarf, as shown in Figure 5, is usually covered in lubricants from machining processes; thus, it is left to strain for at least 24 hours so that excess lubricants may be gravitationally removed. Then, the swarf is cleaned in acetone (C_3H_6O) baths with ultrasonic waves projected to remove lubricants even in intricate spaces within the swarf; which is executed in an ultrasonic bath (Ultrasonic Cleaner) according to the parameters stated in Table 1.

Table 1. Aluminium Swarf Cleaning

Removal of	Solution Used	Apparatus
Excess Lubricants	none	120 Mesh Screen (~125µm)
Remaining Lubricants	Acetone (2ml/g of Al. swarf per-wash)	Ultrasonic Bath (1 hour/wash)
Acetone	none	45µ Mesh Screen / Metal Tray

Figure 4: Cleaned Aluminium Swarf; free of lubricants (dry)

Figure 5. Soaked with lubricant aluminium swarf; sticks to container walls

Figure 6: Cleaned Aluminium Swarf

Figure 7. Blender-ed Aluminium Swarf

Table 1: Aluminium Swarf Ball Milling Parameters

Item	Detail
Container (250ml)	Zirconia (ZrO_2)
Grinding Media	Zirconia (ZrO_2) 10 mm x 36 pcs
Aluminium Swarf	±70 g
Speed	370 RPM
Run	3 mins
Pause	27 mins
1 Operation Cycle Set	5 run/pause cycles
Process Control Agent (PCA)	None

After the aluminium swarf is completely dry of acetone (Figure 4), a common household blender is used to reduce the average size of the swarf from about 9 mm (Figure 6) to 3mm (Figure 7) in length. This is to help minimise the milling time. The milling parameters are as shown in Table 2. After completing the mill, the pulverised aluminium is sieved at 45 and 600 Mesh to remove the grinding media and collect the particles collected at the bottom side of the test sieve, respectively. Then, all the remaining aluminium is subjected to milling again with parameters provided in Table 2 to obtain aluminium pulverisation down to about 25 µm and less. The set of milling cycle is dependent on the remaining aluminium left for pulverisation.

Results and Discusision

Figure 8 depicts the pulverised aluminium condition after 2 (two) operation cycles where a white silver powder is collected before being sieved with the 600 Mesh test sieve. The collection of fine powder is often performed after 2 to 4 operation cycles, depending on the conceivable size of the powder caught above the mesh screen. As far as the eyes could see, the particles seem to be of polygenic and irregular shapes. A large portion of the pulverisation is still visibly large (±300 µm) with a mix of tinier particulates. These large particulates will be caught above the 600 Mesh screen to undergo more milling.

It takes a long time (7.5 hrs minimum) to homogenously pulverise aluminium using the Planetary Ball Mill since aluminium is a ductile material with high thermal conductivity. Ductility is the measure of a material's ability to be stretched into a wire and aluminium’s ductility increases up to a certain temperature; which takes longer to pulverise since the extremely rapid movement of the grinding media inside the container (Figure 9) generates heat that is rapidly absorbed by the aluminium.

Figure 8: Sample of Pulverised Aluminium after Two Operating Cycles

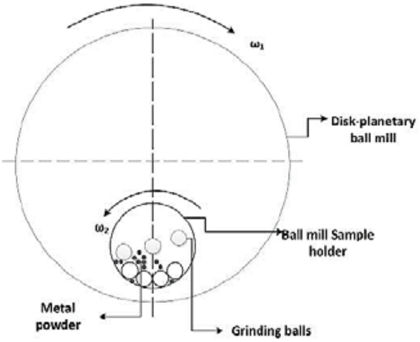

Figure 9. Planetary Ball Mill Schematics [11]

Under the Scanning Electron Microscope (SEM) image as shown in Figure 10, the powder is observed to be irregular in shape with really low aspect-ratios (elongated and/or rough). However, it is significantly refined in size and shape from its original condition i.e. prior to pulverisation. The surface of the powder particles seems to be rough which indicates constant high energy contact to be broken into smaller sizes. Although it is not as smooth or close to spherical shapes as the commercially pure aluminium powder (Figure 12), it is far smoother than the flaky texture of aluminium pulverised with stearic acid as PCA and 10 mm grinding media, as seen in Figure 11.

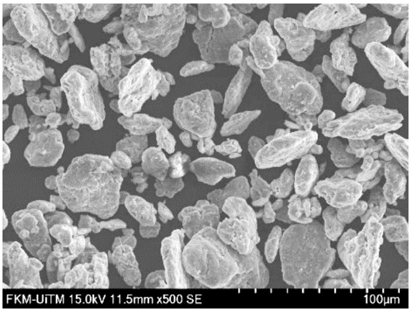

Figure 10. Aluminium powder pulverised without PCA; 10 mm and 1 mm grinding media

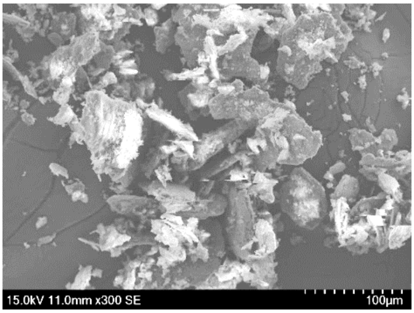

Figure 11. Aluminium powder pulverised with PCA; 10 mm grinding media

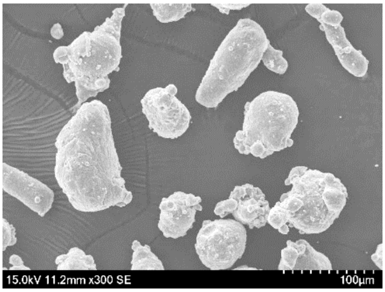

Figure 12. Particle shape of commercially pure aluminium 6061 powder

Upon sieving with the 600 Mesh test sieve, using a Laser Diffraction Particle Size Analyser (LDPSA), the particle size distribution shows that the particles collected as seen in Table 3. As the LDPSA assumes all particle tested is spherical, it provides results in diameters. The graph in Figure 13 shows poly-dispersed results; which means that there are various sizes of particles where the tiniest sizes obtained are between 2.387 µm and 2.703 µm. In common terms, the LDPSA test found that only 10% of the aluminium powder is smaller than 18.056 µm, and the majority (90% or D90) of the powder is smaller than 61.645 µm. While half of the powder is smaller than 34.829 µm and the other half is bigger than 34.829 µm. This may be due to the amplitude applied when using the Vibratory Sieve Shaker; which is at 0.3 mm. This allowed particles of larger sizes to pass through. Another reason to why larger particles passes through the 0.025 mm meshed screen is maybe due to the irregularity in shape of the powder particles; where the larger particles have the smallest of their width, as shown in the SEM image in Figure 14.

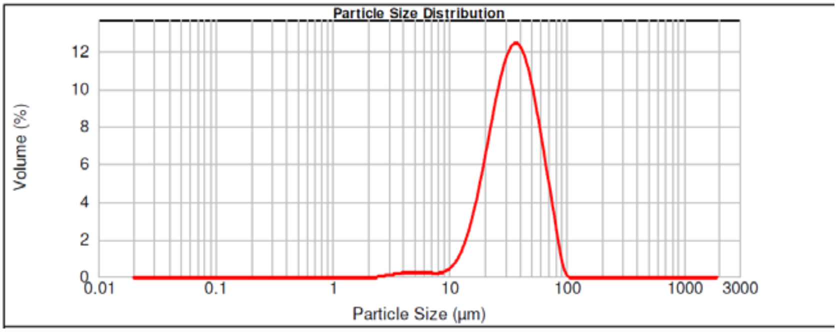

Figure 13: LDPSA results showing the aluminium powder particle size distribution

Table 3. LDPSA results for sieved aluminium powder at 600 Mesh (0.025 mm)

Mean Particle Distribution	Value (µm)
D10	18.056
D50	34.829
D90	61.645

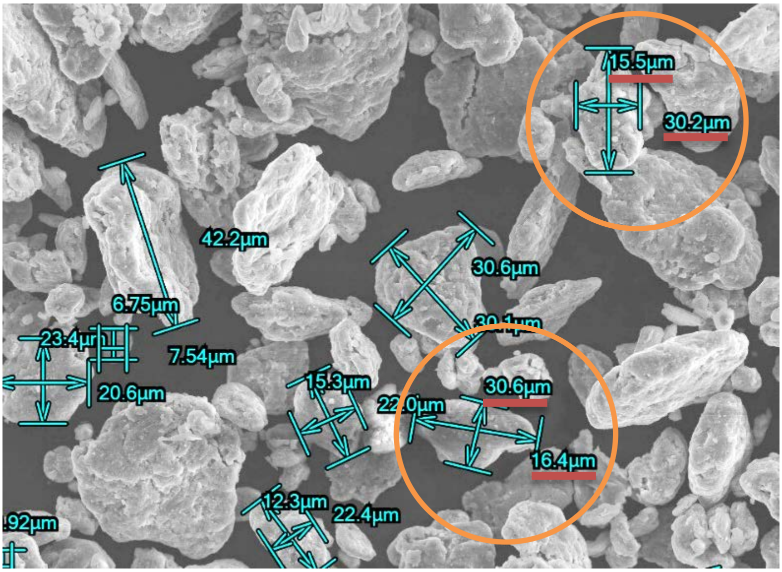

Figure 14: Large particles with their smallest widths highlighted in a SEM image

The X-ray powder diffraction (XRD) analysis done on the pulverized aluminium swarf and commercially pure aluminium powder are depicted in Figure 15. The XRD analysis only detected and shows peaks of aluminium (Al) crystalline in the commercially pure aluminium powder whilst detecting Al and silicon (Si) crystalline in the pulverised aluminium swarf. In other words, the XRD results are showing that the pulverised aluminium swarf is almost free of contaminants and is almost as pure as the commercially produced aluminium powders. To fortify the assumption, a supporting test is performed.

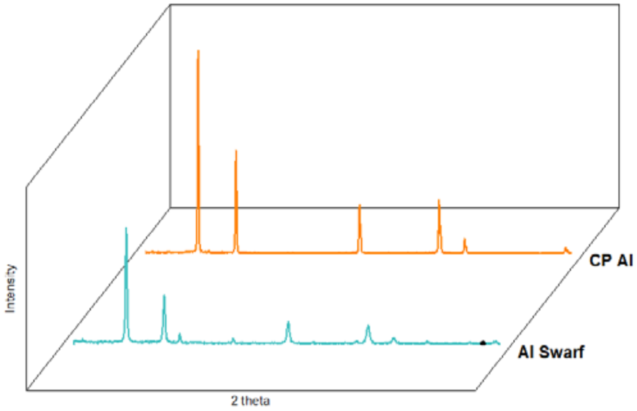

Figure 15: XRD results of Pulverised Aluminium Swarf and Commercially Pure Alumnium Powder

Table 2: XRD peak crystalline present in pulverised aluminium swarf and commercially pure aluminium powder

Crystalline Peak Presence	Al	Si
Pulverised Aluminium Swarf	Yes	Yes
Commercially Pure Aluminium	Yes	No

From the Energy-dispersive X-ray Spectroscopy (EDX) analysis, it confirms the presence of Al in the powder with traces of Si in the pulverised aluminium swarf and solely Al in the commercially pure aluminium powder found via XRD analysis. In justifying the presence of Si in the pulverised aluminium swarf, it may come from the abrasive cutting tool during swarf formation; which sticks to the aluminium swarf. Besides that, it may have also come from the ball mill grinding media since silica sand is used for cleaning purposes. The silica sand particles (in nanoparticles) might have been caught in between the grinding media molecules.

Table 3: EDX results of Pulverised Aluminium Swarf and Commercially Pure Aluminium Powder

Weight %	Aluminium	Silicon
Pulverised Aluminium Swarf	91.4	8.6
Commercially Pure Aluminium	100	0

Conclusion

In conclusion, it is possible for fine (50 µm >) aluminium powder to be produced via ball milling without PCA and inert gas purging; provided that it is milled with 10 mm sized grinding media at 370 RPM in 3 minutes of run time and 27 minutes of cooling down for at least 7 hours, continuously. The pulverised aluminium swarf has an almost pure (91.4 wt%) condition when compared to a commercially pure aluminium 6061 powder which is 99.99 wt% pure.

Although the particle shapes are irregular, they have a better chance of being injected compared to the pulverisation of aluminium with the use of PCA but without argon gas purging that produced almost needle-like and flaky textures; which have even higher tendency to halt the flow of injection moulding. This means, the sustainability of irreplaceable natural resources of aluminium could be achieved when reusing its swarf in producing high quality and high-performance parts via MIM such as in electronic components of medical apparatus, automotive, telecommunication, IT technology fields etc. serving as lightweight and high thermal conductive components. Aside from that, ball milling does not use as much energy as gas atomisation in making aluminium powder and emits almost no hazardous gases that pollute the atmosphere compared to making ingots in furnaces. Which means ball milling metal swarf for powder production actually helps to reduce energy consumption and minimising pollution altogether.

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