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ADVANCED MANUFACTURING

Development of a Net Zero Route for the Circular Production of Additive Manufacturing Powders

The research centres on the development of a Net Zero route for the sustainable production of metal additive manufacturing (AM) powders. In particular, the study involves recycling of waste machining chips to produce usable AM powders via solid-state crushing/ball milling (BM) at room temperature. Experimental work deals with the conversion of AA5083-H111 aluminium chips into powders using BM, followed by powder characterisation. It is observed that the particle size distribution and the powder morphology are influenced by the chip's length scale and BM parameters (such as ball-to powder ratio, ball diameter, milling speed and time). Finally, a framework of a novel circular hybrid manufacturing process chain to fabricate high value AM parts from the produced powders is proposed.

Keywords:
Net Zero, sustainable manufacturing, additive manufacturing, ball milling, aluminiums.

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INTRODUCTION

The United Nations Framework Convention on Climate Change (UNFCCC) in their annual Conference of Parties (COP) addresses the issues of climate change by reducing greenhouse gas emissions and accelerating the Paris agreement. In 2015, the United Nations have adopted 17 Sustainable Development Goals (SDGs) as part of the 2030 Agenda for Sustainable Development. Of these, SDG 12 that states “Ensure sustainable consumption and production patterns” [1] is directly relevant to the theme of the current research activities on sustainable manufacturing, undertaken by the High-Value Manufacturing Group at Cardiff University. The research strategy further aligns with the UK Government’s ‘Net Zero’ targets to reduce the net CO_2 emissions from energy and industrial processes via greater promotion of circular economy and sustainable manufacturing [1, 2].

The global additive manufacturing (AM) market is expected to expand at a compound annual growth rate of 20.8% from 2022 to 2030 [3]. Research evidenced that metal powder cost is the largest continuous expense through the life of an AM machine. However, the standard metal AM powder production processes involve melting and atomisation of raw billets/ingots via water, gas, and plasma atomisation [4]. These processes and the powder supply chain makes them expensive. Substantially these techniques incur significant amount of energy consumption and generate carbon footprint. A recent study has compared the environmental impacts of metal AM processes against the conventional manufacturing (CM) technology. For example, 50-192 CO_2eq. is released to process aluminium material per kg by AM while CM releases 0.036-9.6 CO_2eq. compared to casting, extrusion, rolling, and wire drawing processes [5]. AM typically has a significantly higher carbon footprint per kilogram of material, sometimes by a factor of 10 or more. When accounting for embodied impacts in the materials, the environmental impact of AM can be multiplied by 1.4 to 8 times. However, this may not be an equitable comparison, as AM has the capability to produce certain components in a single step that would otherwise require multiple steps in conventional manufacturing processes [5]. A subject of exploration within this domain is the investigation of how employing remanufacturing or recycling purposes to this technology may diminish the ecological and economic impact of a component.

Research has been undertaken to recycle machining chips for powder metallurgy route [6, 7], and applications such as powder consolidation compaction and sintering [8–10]. With regard to the AM applications, ball milled (BM) chip powders or unprocessed chips were mainly tested in single-track melting via directed energy deposition (DED) [11, 12] and laser powder bed fusion (LPBF) processes [13]. The evidence of the fabrication of complete AM parts from ball milled powders is however extremely limited [14]. The majority of research on single-track melting/full part fabrication involved the DED process, partly because of the less stringent requirement on powder properties (sphericity, flowability, packing density…, compared to that needed for the LPBF process [15]. The current research therefore aims to generate AM powders via ball milling, for LPBF applications. A novel Circular Hybrid Manufacturing (CHM) route is developed to process and utilise BM powders in fabricating functional post-processed LPBF parts. Figure 1 shows the schematic of the CHM process chain.

MATERIALS AND METHODS

The chips of AA5083-H111 aluminium alloy of ~1-3 mm length scale was obtained from conventional milling operation on a vertical CNC milling machine. A representative image of the chips is shown in Fig. 2a. A 4-tooth carbide end mill cutter with 16 mm dia. was used for the milling operation at 85 m/min, 0.24 mm/rev feed rate and an axial depth of cut of 0.5 mm. The machined chips were cleaned with acetone and isopropyl alcohol in an ultrasonic bath to remove impurities originated from cutting fluid and grease. The cleaned chips were then dried in an oven at 90°C for 60 min to eliminate the moisture content. Subsequently, the chips were ball milled in a planetary ball mill, made by MECHMIN, Ltd., India (Fig. 2b).

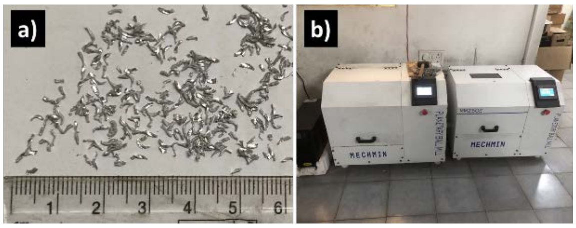

Fig. 2. a) Raw AA5083 chips, b) MECHMIN Planetary ball mill.

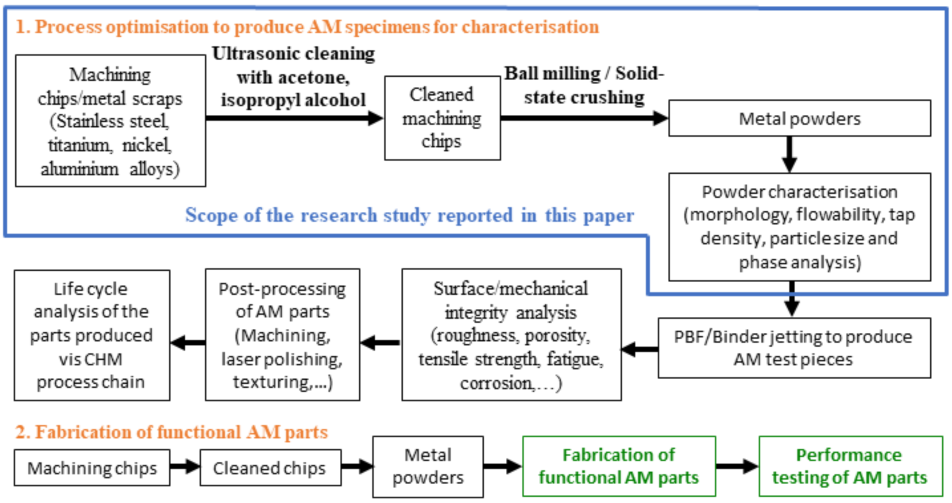

Fig. 1. Schematic of the CHM process chain.

On the dual working station ball mill, two hardened stainless steel cylindrical vials/jars with 250 ml and 100 ml volume and three different ball diameters (20 mm, 10 mm, 5 mm) were used. Approximately 50-60% of the jar volume was filled with the balls and the chip material. For BM operation, 15 balls of 20 mm dia., and 50 balls of 10 mm dia. were used in each of the 250 ml vials, and 250 balls of 5 mm dia. were used in each 100 ml jar. Three different ball-to-powder ratios (BPR), such as 15:1, 20:1, and 30:1 were utilised in different stages of BM. A 300 rpm BM rotational speed was typically used with 10 and 20 mm balls, however an exploratory trial involved 500 rpm speed when using 10 mm balls. A reduced BM speed of 150 rpm was employed when using the 5 mm balls.

There sets of multi-stage BM trials, involving 2 or 3 stages per set were undertaken in Phase 1, details given in Table 1. An on/off cycle of 15 min was applied when BM to avoid excessive heating of the milling media. So, the total machine cycle time for 30 min of BM run was 45 min, and 105 min for 60 min BM run.

Sets and Stages		BPR	Ball diameter (mm)	Jar volume (ml)	BM speed (rpm)	BM time (min)
Set 1.1	Stage 1	20:1	20	250	300	30
	Stage 2	20:1	10	100	300	30
	Stage 3	20:1	5	100	150	90
Set 1.2	Stage 1	30:1	20	250	300	30
	Stage 2	30:1	10	100	300	30
	Stage 3	30:1	5	100	150	90
Set 2.1	Stage 1	15:1	20	250	300	30
	Stage 2	15:1	5	100	150	90
Set 2.2	Stage 1	20:1	20	250	300	30
	Stage 2	20:1	5	100	150	90
Set 2.3	Stage 1	30:1	20	250	300	30
	Stage 2	30:1	5	100	150	90
Set 3	Stage 1	15:1	20	250	300	60
	Stage 2	10:1	10	250	500	30

Table 1. Phase 1 multi-stage BM parameters.

After Stage 1 in each set, ball milled powders were sieved to <180µm and used for the next successive stages. It was observed in Set 3, that although a higher BM speed, i.e., 500 rpm, was safe to be used with 10:1 BPR, however the same speed caused considerable noise and vibration when used with larger balls (such as 20 mm).

Based on the visual inspection, particle size and powder morphology results from the Phase 1 BM powders, the Phase 2 BM parameters were selected and are shown in Table 2.

Sets and Stages		BPR	Ball diameter (mm)	Jar volume (ml)	BM Speed (rpm)	BM time (min)
Set 1	Stage 1	15:1	20	250	300	60
	Stage 2	10:1	10	250	300	30
	Stage 3	10:1	5	100	150	60
Set 2	Stage 1	15:1	20	250	300	60
	Stage 2	10:1	10	250	500	30
	Stage 3	10:1	5	100	150	60

Table 2. Selected BM parameters in Phase 2.

Assessing the scope of the study of the BM process to reduce the processing time and produce powders in sufficient quantity a 10:1 BPR was selected for Stage 2 and Stage 3 in both sets.

The powder morphology was analysed using a Carl Zeiss FEG scanning electron microscope (SEM). Particle size distribution was obtained via mechanical sieving with three sets of sieve size - 63, 150 and 180 µm. Phase detection on the powder particles was carried out using a Bruker D8 Advance X-ray diffractometer (XRD) with a Cu-Kα target, 0.03° step size, 0.5 s/step scan speed, 40 kV voltage and 30 mA current, within a 2θ range of 20°-90°.

RESULTS AND DISCUSSIONS

In the planetary ball milling technique, the process parameters play a vital role in producing fine powders. The particle sizes are influenced by BPR, BM time, and BM speed [16]. Fig. 3 shows the powder morphology of the BM AA5083 powders at different stages as mentioned in Table 1 and 2. The particles obtained with the 20:1 BPR in all stages were flattened and irregular in shape, possibly due to plastic deformation (Figs. 3a and 3c).

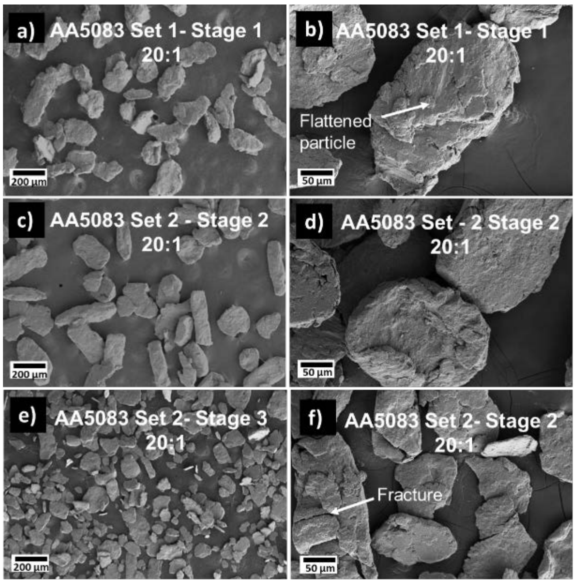

Fig. 3. SEM images of BM AA5083 powder particles after each stage of Set 1.1

It was observed adopting a multi-stage BM process aided in reducing the particle size. This is also recommended in [12]. Indeed, the particle size reduced from Stage 2 to Stage 3 in Phase 1, when using smaller 5 mm balls (Figs. 3e and 3f). This observation is corroborated by the particle size distribution analysis. In Phase 1, ~18% (by weight) of the BM particles were <180 µm after Set 1-Stage 1 with respect to the total BM chip weight. In contrast, ~63% of the BM powders were <180 µm after Set 2 Stage 2 in Phase 2. The particle size distribution in Fig. 4 reveals that ~70% of the particles were <180 µm after Set 2-Stage 3 BM. SEM images further reveal plastic deformation on the particles. This is possibly because the AA5083 alloy is typically a ductile material. A few cleaved fractured regions can also be seen which could be attributed to the material's strain hardening ability due to the presence of ~4-4.9% Mg in the alloy. Phase analysis on the aluminium chips and the BM powders using XRD displayed Al and Al_2O_3 peaks at the standard 2θ positions, see Fig. 5.

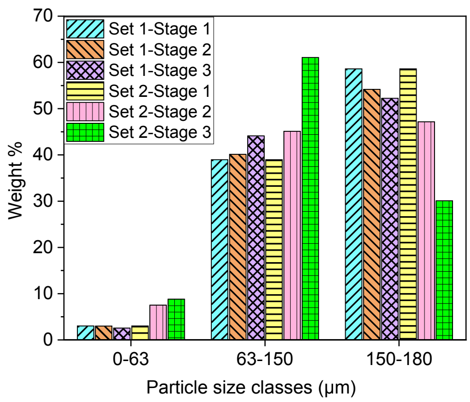

Fig. 4. Particle size distribution of BM AA5083 powders via sieving, obtained in Phase 2.

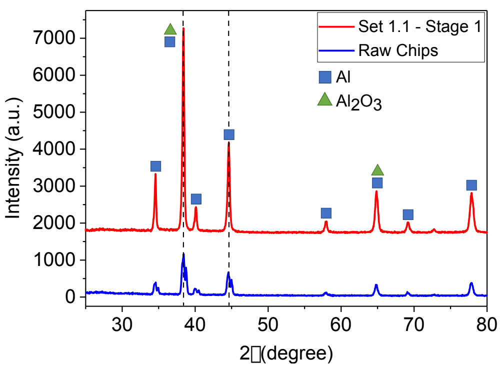

Fig. 5. XRD analysis of AA5083 powder particles.

Following the successful generation of powders via BM from machining chips, the next phase of the research aims at building AM parts using an in-house LPBF system. A new reduced build volume (RBV) kit has been designed and fabricated (Fig. 6) in order to be used in the in-house LPBF system.

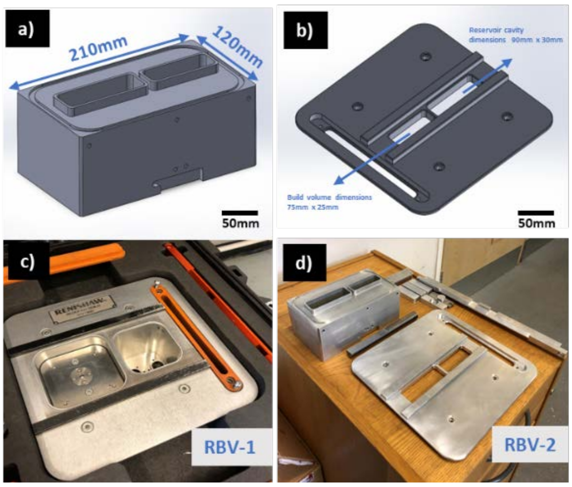

Fig. 6. Design and fabrication of the RBV kit for the in-house LPBF system: a) Build block, b) Top plate, c) Existing RBV kit (80 mm × 80 mm), d) Newly fabricated RBV kit (25 mm × 75 mm).

CONCLUSIONS

The research outlined in this paper is the cornerstone for implementing the net zero strategy to the circular manufacturing of AM powders. This work illustrates how BM can convert machining chips into powders suited for LPBF process. The results indicate that it is important to optimise the BM parameters (such as BPR, BM time, rotational speed, ball diameter and material) to produce powders with the targeted particle size and shape. The composition of the chips and their length scale also showed a considerable impact on the effectiveness of the BM process as well as on the particles' morphology and size distribution. SEM images reveal flattened particles in Stage 1 of all trial sets, which became more spherical with reduced particle size when subject to multi-stage BM. Nonetheless, greater particle sphericity, suitable for LPBF process, is yet to be achieved. The next step of the current work will be the fabrication of AA5083 AM test pieces (particles sieved under 180 µm) on the in-house LPBF system. The parts' surface integrity and mechanical properties will be compared with those built using commercial Al powders with comparable properties.

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Conflicts of interest

The authors declare no conflict of interest.

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