UPCYCLING MACHINING CHIPS FOR A CIRCULAR ECONOMY IN ADDITIVE FRICTION STIR DEPOSITION

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INTRODUCTION

Selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), powder bed fusion (PBF), and directed energy deposition (DED) represent widely used additive manufacturing (AM) techniques for producing metals and alloys [1-4]. These methods involve the use of high temperatures and substantial energy, employing either a laser or electron beam to selectively melt powder materials, which are either contained in a powder bed or supplied through feed nozzles. Despite advancements in these beam-based AM processes, they still face challenges like high energy consumption, material constraints, lengthy processing times, and significant costs [5, 6, 7]. To address these issues, solid-state AM processes have been developed, which do not require melting [8, 9]. One such process is additive friction stir deposition (AFSD), which is derived from friction stir welding (FSW). AFSD utilizes a rotating tool with material feed through the tool to generate frictional heat and plastic deformation, allowing metals to be deposited layer by layer in a solid state [10]. The process reduces defects, such as porosity and cracking typically associated with melting and solidification, and provides dense parts [11, 12, 13].

AFSD is particularly advantageous for fabricating or repairing high-strength, heat-sensitive alloys, such as aluminum, titanium, and steel, which are otherwise challenging to process with conventional fusion-based methods. AFSD not only offers a sustainable pathway to metal component production, but also enables the upcycling of metal waste by converting machined metallic chips back into valuable finished products. Through severe plastic deformation of the materials in solid state, AFSD has been shown to give improved mechanical properties comparable with those of the wrought material in the final printed parts. This makes AFSD an attractive choice for aerospace, automotive, defense, and marine applications, where material integrity and performance are critical.

Agrawal et al. [14] explored the impact of processing variables on the microstructure and mechanical properties of Ti6Al4V deposited using AFSD feedstock derived from machining chips. The tool rotational rate and traverse speed significantly influenced the microstructure and therefore affected material strength and elongation, as well as tool wear. Jordon et al. [15] utilized an auger-based feeding system to directly deposit dry-machined aluminum alloy 5083 (AA5083-H131) chips. The microstructure of the deposition revealed a fine, equiaxed grain structure and exhibited wrought-like material properties. Beck et al. [16] deposited solid Al-Mg-Mn alloy (AA5083-H131) and AA5083 feedstock from machining chips to compare the mechanical properties of wrought, solid bar, and recycled feedstock. An increase in both ultimate and fatigue strength for the AFSD recycled chip parts relative to wrought material was observed due to significant grain size reduction. Automotive aluminum chips were ultrasonically cleaned and then die-compacted to produce feedstock by Yoder et al. [17]. The strain-hardened deposit showed an increased elongation of 17.8% as compared to 1% in the wrought material.

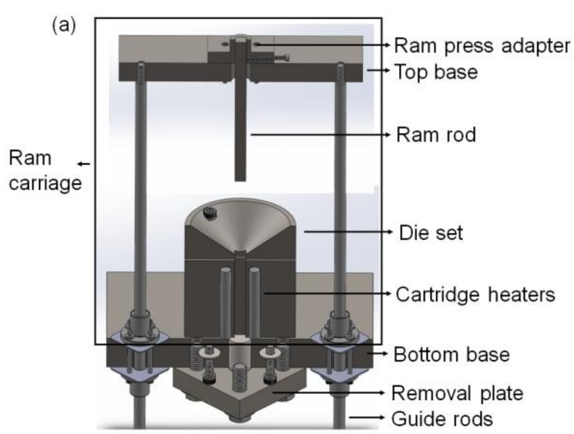
CHIP COMPACTOR DESIGN

This paper describes a chip compactor design for use in a hydraulic press. An A2 tool steel ram was used to produce AA6061 feedstock bars with 100 mm × 12.7 mm × 12.7 mm dimensions. Compressive mechanical forces and in-process heating were combined to consolidate as-machined aluminum chips into solid feedstock.

The compactor was integrated with a 20-ton hydraulic press and consists of a ram carriage and die set. The initial chip compactor design featured a solid cylindrical die set, as shown in Figure 1, with the option of stacked dies to increase stroke length. The ram carriage aligns the ram rod with the die set during the press motion. The carriage assembly includes a ram press adapter, top base, ram rod, and the die set, as illustrated in Figure 1 (a) schematic. The A2 tool steel ram rod has the capability to withstand up to 27 tons of force due to the fixed top base that minimizes deflection. The die features a square through-hole machined to the desired feedstock cross-section of 12.7 mm × 12.7 mm using wire electric discharge machining (WEDM). The entire structure, including the ram carriage and die set, was secured in place through a bottom base and guide rods.

To begin compaction, the compactor assembly shown in Figure 1 was mounted onto the press to align the ram rod with the die. Next, the aluminum chips were manually fed into the die. The chips were then compacted under cold working conditions at room temperature or warm conditions using integrated cartridge heaters. After the final compaction, a dwell was commanded before final feedstock extraction.

This initial design had some limitations, as illustrated in Figure 2. These included buckling of the ramrod due to misalignment issues and the compacted rod getting stuck between the die set, which made extraction difficult and led to the rods fracturing into pieces.



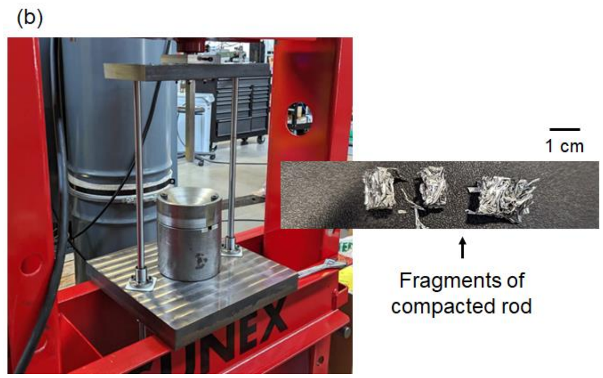


FIGURE 1. (a) Schematic of the chip compactor assembly and (b) chip compactor mounted on the hydraulic press and fragmented feedstock bar (inset).

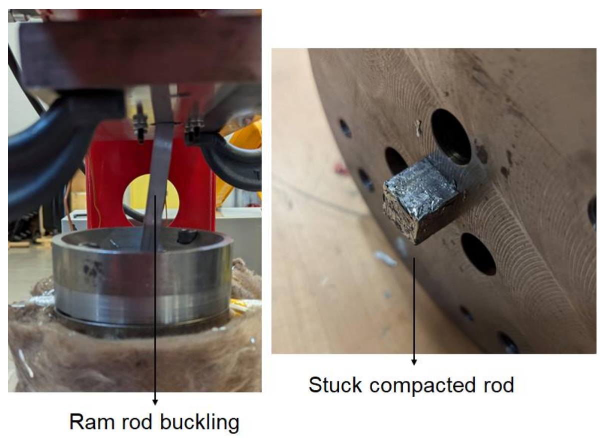
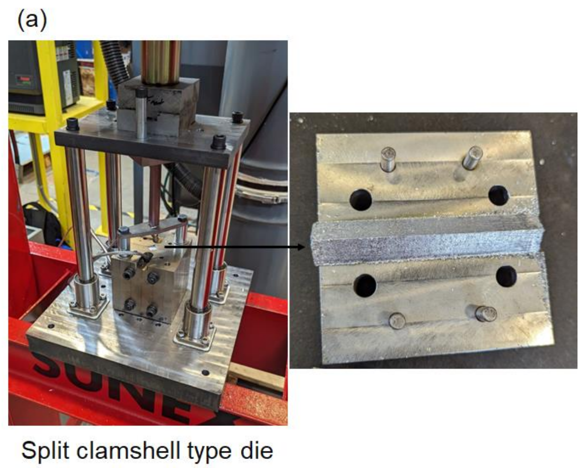
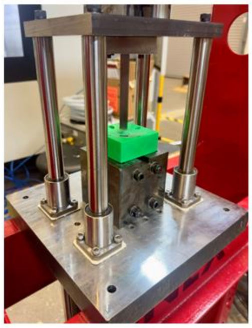


FIGURE 2. Issues with the initial chip compactor design.



(b)



Die with an extension

FIGURE 3. Split clamshell type compactor design with the ensuant compacted rod.

In order to improve performance, the die set was redesigned as a split clamshell type and included a guiding bracket for precise alignment of the ram rod into the diamond die cross-section. It enabled convenient extraction of the compacted rods without fracture from the die halves after the compaction process. Figures 3 (a) and (b) describe the modified die design and show compacted bars. Subsequent design modifications included a 50.8 mm 3D printed extension block to maximize the available stroke length on the press.

RESULTS AND DISCUSSION

In order to obtain consistent compacted bars with acceptable relative densities, the parameters for the compaction process were identified and optimized. The parameters included build force, final force, chip morphology, heat, and cycle time. The force applied during each compacting cycle, including the addition of new chips, is referred to as the build force. The final force is the amount of force applied at the end of the process to optimize the integrity of the compacted bars. Build force was seen to have most significant impact on the quality of the compacted bars, where 6 tons of build force was selected as the optimum value based on the resultant bar quality and processing time. The variation in relative density for the compacted bars with applied build force is shown in Figure 4. Furthermore, the final force of 6 tons was applied multiple times to ensure consistency in the process. The magnitude of the final force was seen to have little effect on the relative densities of the compacted bars.

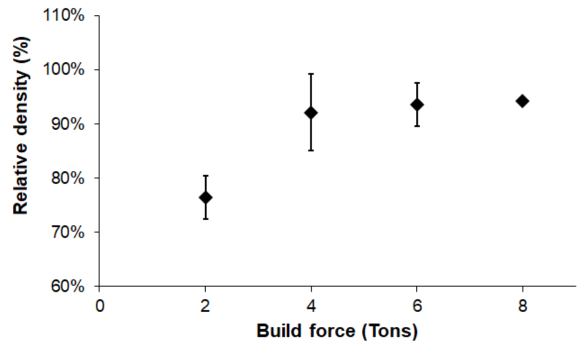


FIGURE 4. Variation of relative density with build force.

Different chip morphologies were obtained from various machining processes like milling, grinding, and power saw cutting; see Figure 5. The chip morphology was seen to have a direct impact on the cycle time. Finer ground chips did not endure compression well and fractured into parts, while also leading to increased cycle times. Ribbon chip morphology, see Figure 5 (a), generated by milling Al 6061 gave consistent compacted bars under cold working conditions with relative densities between 85% and 95%. The application of heat using the integrated cartridge heaters gave 100% relative density, but also significantly increased the cycle time.

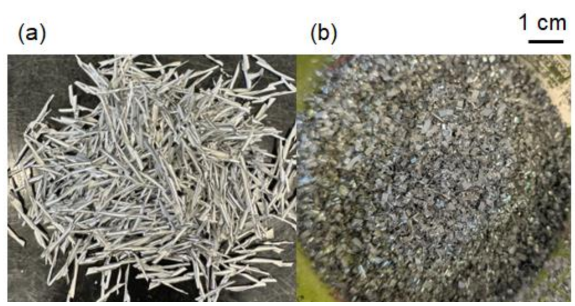


FIGURE 5. (a) Ribbon-like chip morphology and (b) powdered bandsaw chips.

Figure 6 shows the progression of compacted bar quality with die redesign and optimization of process parameters. Consistent compacted bars having 86% to 100% relative density were obtained for ribbon chip morphology with 6 tons of build force, and 6 tons final force applied four times with or without the application of heat.

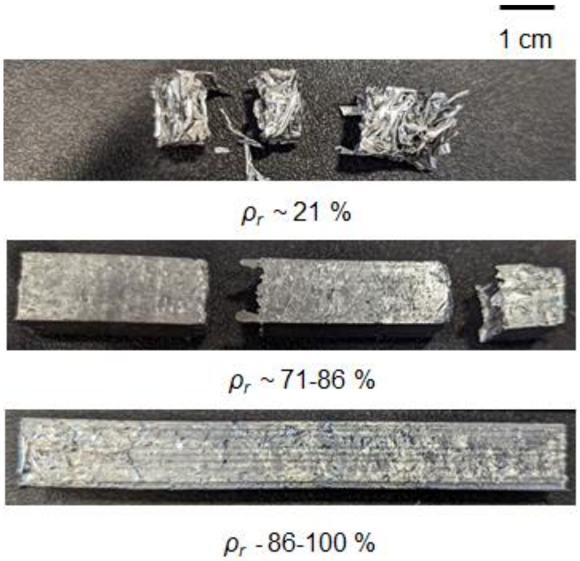


FIGURE 6. Progression of resultant compacted bars with die redesign and process parameter optimization (ρ_r – relative density).

CONCLUSION

The paper presents a chip compactor for repurposing and upcycling machined aluminum chips into usable feedstock material for AFSD processes. The design incorporates a ram carriage and split clamshell-type die set onto a hydraulic press. The application of compressive mechanical forces under cold and warm working conditions demonstrates the system's potential for industrial recycling. Through optimization of process parameters such as build force, final force, and chip morphology, consistent compacted bars having relative densities of 86% to 100% were successfully obtained. Fully dense bars were obtained after heating the system to 300°C and holding it under constant pressure for 15 minutes. AFSD generally has a high tolerance for feed material quality due to the feedstock material undergoing severe plastic deformation before deposition. As such, bars with 70% to 80% relative densities can also be used to obtain fully dense deposited parts. While the system has integrated heating for use when needed, the application of heat significantly increases the cycle times. In the current streamlined operating procedure, the use of heat has been eliminated for preparation of compacted bars for AFSD.

The objective of this research is to achieve sustainability in AFSD and move towards a circular economy model throughout additive manufacturing, as illustrated in Figure 7.

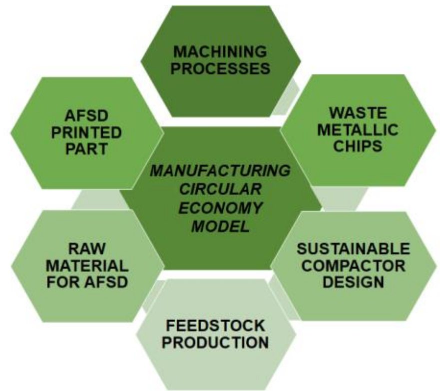


FIGURE 7. Schematic of the circular economy model in machining chips recycled feedstock production.

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