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A NEW METHOD FOR UPCYCLING MACHINING CHIPS FOR ADDITIVE FRICTION STIR DEPOSITION

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Abstract

Additive friction stir deposition (AFSD) uses a rotating tool to generate frictional heat and plastic deformation, allowing metals to be deposited layer by layer onto a substrate without melting. This solid-state process offers an opportunity for upcycling metallic chips collected from machining operations to produce feedstock rods. Accordingly, this work presents a chip compactor design integrated into a hydraulic press through a die set and ram carriage. Through the application of controlled compressive mechanical forces under both cold and warm working conditions, the system can produce aluminum (Al6061) rods from machining chips with 86% density relative to wrought Al6061. The chip compactor design is a step forward toward achieving sustainability in AFSD by adopting a circular economy model.

Keywords: Additive friction stir deposition, solid-state additive manufacturing, metal recycling, sustainability, circular economy.

Introduction

Powder bed fusion and directed energy deposition are two common additive manufacturing (AM) processes for the fabrication of metals and alloys [1]. These processes involve high temperatures and significant energy, using a laser or electron beam to selectively melt powders that are either pre-deposited to form a powder bed or delivered through feed nozzles [2-3]. Even with the rapid advances in these beam-based AM processes, remaining challenges include high energy consumption, material limitations, long processing times, and high costs [4-5]. To overcome these limitations, solid-state AM processes have been developed that do not rely on beams to melt materials [6-8]. Additive friction stir deposition (AFSD) is one such AM process that is based on the principles of friction stir welding (FSW). This technique employs a rotating tool to produce frictional heat and plastic deformation, enabling metals to be deposited layer by layer onto a substrate [9]. AFSD operates in a solid state, which significantly reduces defects associated with melting and solidification, such as porosity and cracking. This results in highly dense, near-net shape parts [10-11]. AFSD is particularly beneficial for fabricating or repairing high-strength, heat-sensitive alloys like aluminum, titanium, and steel, which are difficult to process using conventional fusion-based methods [9, 12-13]. AFSD allows for the upcycling of metal waste by converting metallic chips collected from machining operations into valuable finished products. By keeping materials in their solid state, AFSD preserves the original alloy's mechanical properties and prevents grain coarsening, ensuring excellent mechanical performance in the final product. This makes AFSD an attractive option for aerospace, automotive, defense, and marine applications, where material integrity and performance are crucial.

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, thus, 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 as shown in Figure 1 (a). A fine, equiaxed microstructure was observed and exhibited wrought-like material properties. Beck et al. [16] also 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; see Figure 1 (b). 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.

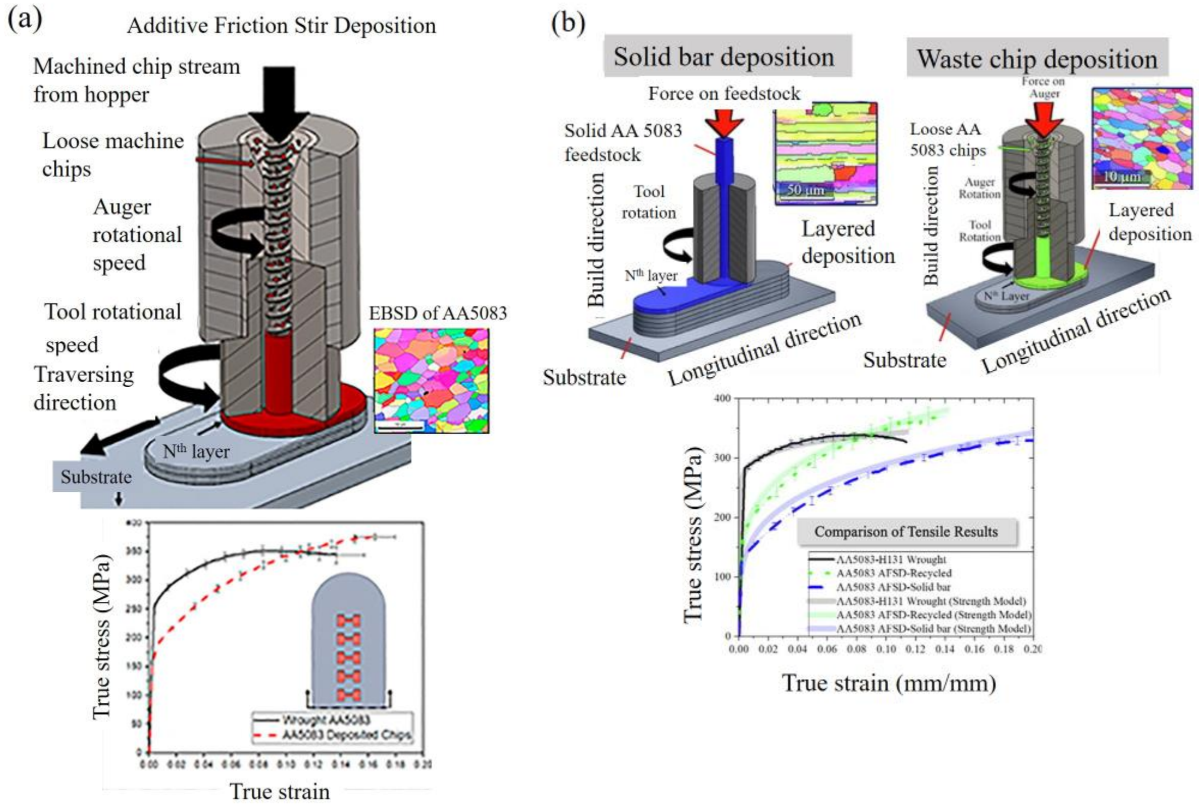

Figure 1. Schematic of direct recycling of AA 5083 machining chips using AFSD by feeding through an auger-based system (a) Jordon et al. and (b) Beck et al.

The recycling of machining chips (or swarf) has also been studied for other AM processes. Sarah et al. [18] explored and established Ti6Al4 swarf as a feasible feedstock material for laser directed energy deposition (L-DED) process. The microstructure of printed samples was seen to vary based on the mechanism of powder formation. Other similar research has shown the successful recycling of steel chips into feedstock powder for printing tracks using L-DED [19-20]. Rui et al. [21] evaluated the properties of recycled 7075 aluminum alloy obtained as scrap from “aircraft graveyards” to demonstrate good resistance to stress corrosion cracking as well as intergranular corrosion. The authors also highlighted the environmental and industry challenges posed by retiring aircraft and emphasized the need for advanced management solutions.

Experimental design

This paper describes a chip compactor design for use with a hydraulic press. An A2 tool steel ram was used to produce 10×1.27×1.27 cm Al6061 feedstock bars. Compressive mechanical forces and in-process heating were combined to consolidate as-machined aluminum chips into solid feedstock bars.

The compactor, comprising a ram carriage and die set, was integrated with a 20-ton hydraulic press. 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 die set. With a fixed top base that minimizes deflection, the A2 tool steel ram rod can withstand up to 27 tons of force. The die featuring a square hole machined to the desired feedstock cross-section of 1.27×1.27 cm using wire electric discharge machining (WEDM) and surrounded by three cartridge heaters was bolted to the bottom base plate. This design consideration allows for the stacking of dies to accommodate increased lengths of compacted rods up to 30 cm. A titanium removal plug along with titanium washers isolated the die from the base. Additionally, the die can also be wrapped in fiberglass insulation to reduce the rate of heat transfer between the die components and the environment during the heating process. Finally, 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 2 (a), was mounted onto the press to align the ram rod with the die. Next, the aluminum Al6061 chips were fed into the die and compacted at room temperature by applying a gradually increasing pressure. This step was repeated until the entire length of the compacted rod was achieved. The setup was then heated to 300°C using the cartridge heaters and, upon reaching the desired temperature, a final compaction was performed to increase the compaction efficiency. After this final compaction, a dwell was commanded to allow for the system to cool down and then the compacted rod was extracted using a split die strategy. The entire compaction process was also performed without heating.

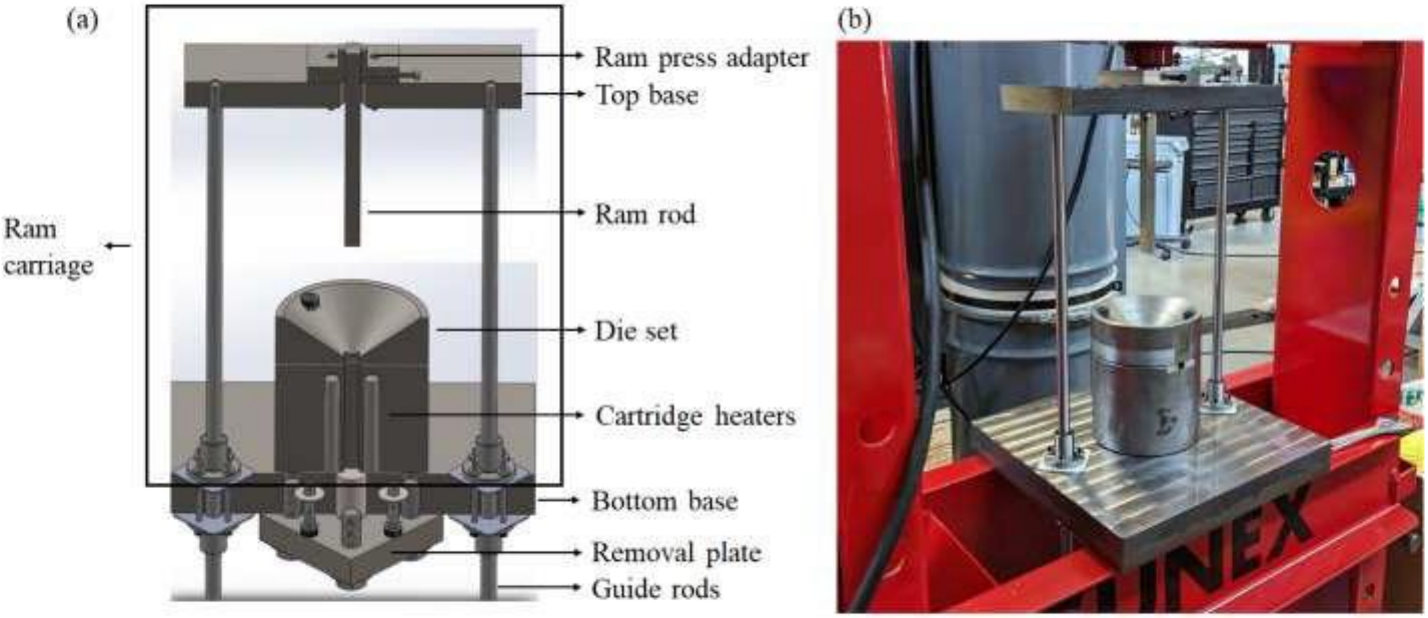

Figure 2. (a) Schematic of the chip compactor assembly cross-section mounted on the hydraulic press and (b) final assembled chip compactor

Results and Discussion

Initial experiments were conducted using Al6061 chips produced by milling with a ribbon-like morphology as shown in Figure 3. The chips were cleaned using an ultrasonic cleaner to remove any residual coolant. Table 1 shows the measured parameters of mass, volume, density, and relative density for each compacted bar over three tests. The measured widths of each portion were greater than the desired feedstock width of 1.27 cm. The relative density measurements were performed using Archimedes' principle for the compacted rods and wrought Al6061 feedstock bars. Test one (bars 1, 2, and 3) produced loosely packed bars with relative densities between 17% and 25% with smaller applied pressures on each compression and no heating. Test two (bars 4, 5, and 6) produced rod portions with relative densities between 70% and 86%, and test three produced a continuous rod with a relative density of 76.3%.

The first compacting test was performed in the absence of heating at room temperature with the ram rod extending only a few centimeters into the die and recording no pressure on the dial gauge of the press when compacting the chips. This test was concluded after determining that the ram rod needed to extend further into the die to produce compressed rods faster and more efficiently. The test produced three segments of loosely compacted rods having relative densities between 17% and 25% as seen in Figure 4 (a). Issues, such as the ram rod misalignment, were identified and corrected for the second set of compacting tests.

Figure 3. As-machined Al6061 chips

Table 1. Initial test results

Bar No.	Test No.	Mass (gm)	Length (cm)	Width - x (cm)	Width - y (cm)	Volume (cm^3)	Density (gm/cm^3)	Relative density (%)
1	1	1.4	1.74	1.33	1.31	3.03	0.46	17.1
2	1	0.8	0.73	1.285	1.29	1.21	0.66	24.4
3	1	0.8	0.825	1.29	1.31	1.4	0.57	21.2
4	2	13.3	3.37	1.29	1.31	5.7	2.33	86.3
5	2	13.9	3.77	1.29	1.29	6.28	2.21	81.9
6	2	3.9	1.21	1.29	1.31	2.04	1.91	70.6
7	3	34.6	10.04	1.3	1.29	16.84	2.06	76.3

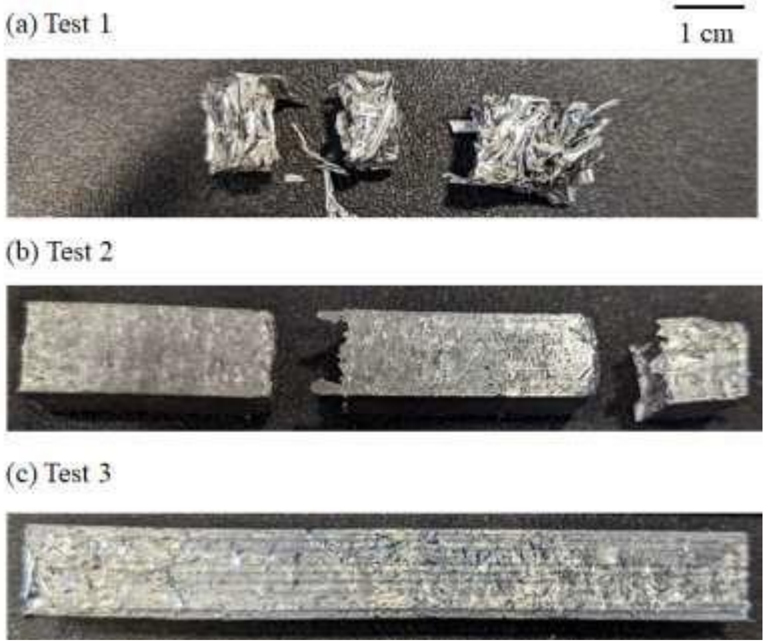

Figure 4. (a) Test 1, (b) Test 2, and (c) Test 3 compacted rods

The second test was also performed without heating, but the ram rod was adjusted to extend further (7.6 cm) into the die and allow for better compaction. The chips were fed into the die and the pressure was increased gradually with intermittent pressure-releasing passes to ensure the ram rod did not get jammed in the die due to excessive pressure. While these tests produced rods having an average relative density of 80%, they fractured into parts upon extraction as shown in Figure 4 (b). Additionally, once about 7.6 cm length rods were produced the ram rod started to buckle after reaching a threshold pressure.

The third test was performed with heating. As with the second test, the chips were fed into the die and pressure was gradually applied with intermittent pressure-releasing passes. The system was heated to 300°C and the rod was further pressed slightly at this state to ensure better compaction. The entire system was then allowed to cool to about 60°C and the rod, shown in Figure 4 (c), was extracted. The compacted rod maintained its integrity and achieved a relative density of 76.3%.

The alignment of the ram rod leading to buckling issues and extraction of the compacted rod were two of the major challenges encountered throughout the initial testing of the chip compactor. Even a slight misalignment of the ram rod caused significant deflection as shown in Figure 5. To extract the compacted rod from the die, a pressure of about 4 tons had to be applied. Additionally, the rod also fractures when shearing forces are applied to push it out from the die causing it to segment to pieces. To avoid these issues in the future, a more robust compactor assembly along with alternate dies has been designed and is currently undergoing testing.

Figure 5. Ram rod alignment and compacted rod extraction issues

Conclusion

Due to severe plastic deformation and inherent material stirring, AFSD not only enables material consolidation but also alters the microstructure while avoiding voids and defects. The outcome is wrought-like mechanical properties in the printed material. AFSD offers a suitable solid-state AM process for machining chip upcycling in the fabrication of 3D preforms. In contrast, fusion-based aluminum recycling offer limited upcycling benefits due to the resulting material microstructure and mechanical properties.

The chip compactor system design in this work is engineered to recycle and repurpose aluminum chips into feedstock material for AFSD processes. The compactor assembly presented here incorporates a die set and ram carriage onto a hydraulic press to produce compacted rods. The compactor is designed to work under cold (room temperature) as well as warm (elevated temperature) working conditions through the use of integrated cartridge heaters. Bars of up to 85% relative density have been achieved. Since the compacted bars undergo severe plastic deformation during the AFSD process, achieving 100% relative density is not crucial. Future work will include compacting titanium and steel chips, mechanical testing, and material characterization of the compacted rods, and printing AFSD parts. The potential of AFSD for supporting circular economy and materials sustainability is a significant opportunity. This research objective is to enhance sustainability in AFSD and promote a circular economy model in manufacturing, as illustrated in Figure 6.

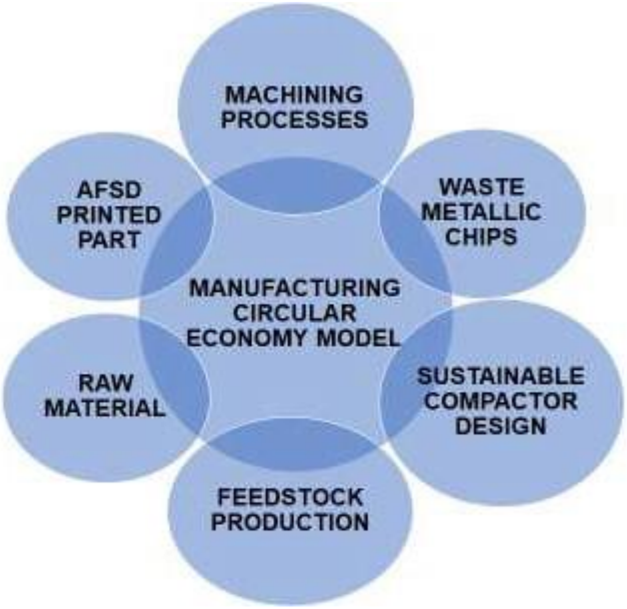

Figure 6. Circular economy model using machining chips for recycled feedstock production

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