# UPCYCLING OF MIXED ALUMINUM ALLOY SHREDDER SCRAP USING SHEAR PROCESSING


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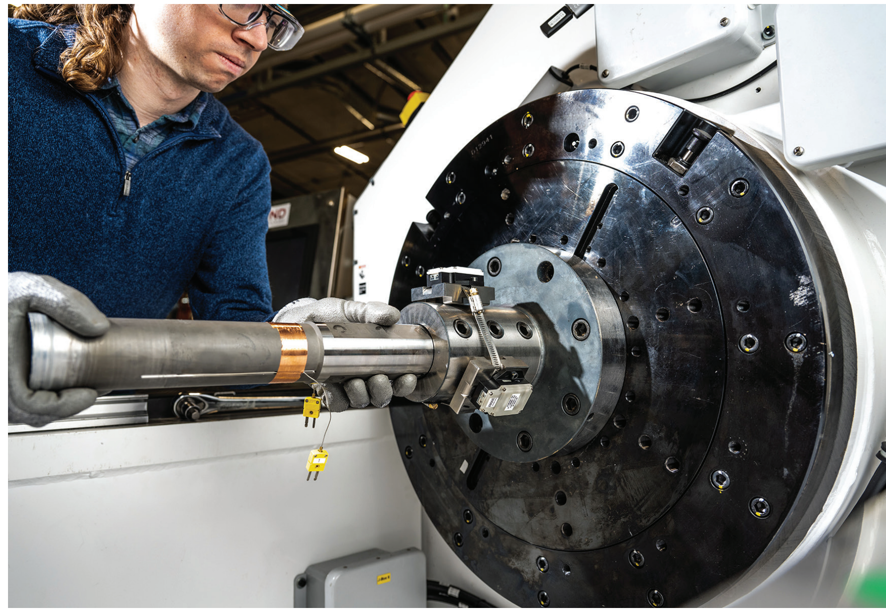
**Scientists at Pacific Northwest National Laboratory won an R&D 100 Award in 2020 for their advanced manufacturing technology, ShAPE, which reduces embodied energy as well as carbon when processing aluminum scrap.**

*Image courtesy of Andrea Starr/PNNL.*

The conservation of critical materials is an increasing area of focus in the United States. In 2023, aluminum was added to the U.S. Department of Energy's (DOE) Final Critical Materials List, which has spurred public and private research into sustainable management of these resources[1]. Additionally, efficiency in manufacturing and the conservation of natural resources are growing concerns to be addressed by lowering global carbon emissions. This is especially pertinent for primary aluminum alloy production, which is energy intensive, requiring 96 MJ of electricity per kg of primary aluminum[2]. Because of these factors, it is essential that more sustainable manufacturing methods for aluminum alloys are developed going forward.

A technology with a large potential impact on carbon emissions is the recycling of post-consumer scrap because it reduces or eliminates the use of primary aluminum. Primary aluminum production requires environmentally damaging mining, and its reduction from ore to metal is energy intensive and has high carbon emissions compared to recycling. To this end, many aluminum production companies are moving toward higher post-consumer scrap use. For example, Hydro launched a wrought aluminum alloy called CIRCAL made with up to 100% post-consumer scrap through advanced sorting of 6060[3]. Rio Tinto has also invested $700 million for a 50% stake in Matalco, an aluminum production company that uses advanced remelting technology to increase the amount of post-consumer scrap in wrought products[4]. And Emirates Global Aluminum recently acquired German recycling giant Leichtmetall as a move toward circularity and increased scrap content in extruded products[5]. Research on the topic of more efficient aluminum utilization and recovery is ongoing.

Even considering recent developments in the recycling of Al scrap, there is still a large amount of post-consumer scrap that is underutilized because of its high impurity content. A challenge to be addressed before the coming scrap wave can be fully utilized is that the tolerance of manufacturing techniques to impurities or off-spec alloy compositions must be increased. Particularly, in 5000- and 6000-series alloys (the most common wrought alloys in durable products), excess iron, copper, and silicon create brittle intermetallics during casting that remain in the extruded microstructure. These intermetallics limit the formability, ductility, and corrosion resistance of the alloy. Concerningly, many of the highest-volume post-consumer aluminum scrap streams such as automotive shredder scrap contain a mix of alloys including both wrought and cast alloys[6]. Their compositions can vary widely depending on geography and the time of year. Because they are mixed, they often contain a high content of multiple alloying elements such as Si and Cu in greater concentrations than are found in typical wrought alloys. They may also be contaminated with non-Al alloys from fasteners and often have a high amount of unwanted elements such as Fe.



ShAPE II machine. Image courtesy of Andrea Starr/PNNL.

An emerging extrusion technology, called Shear Assisted Processing and Extrusion (ShAPE) is being developed at the Pacific Northwest National Laboratory (PNNL) with one application being to shift beyond today's recycling paradigm to upcycle 100% post-consumer aluminum scrap directly into extruded components without the addition of primary aluminum. This new manufacturing approach may allow manufacturers to reach deeper into lower-value scrap streams, to effectively convert scrap that is high in tramp elements into high-performance finished and semi-finished products. Sometimes referred to as Twitch or Tweak, these scrap streams result from the shredding and sorting of automobiles, building materials, appliances, and consumer goods[6]. ShAPE combines the linear axis of conventional extrusion with a rotating extrusion die or billet. The rotation applies a large strain to the material during extrusion, which breaks up large impurity-containing intermetallic particles, reducing their deleterious effects. This has been demonstrated for 6063 machining scrap spiked with excess Fe and for Twitch scrap high in Fe, Si, and Cu, where the strength and ductility were retained for both feedstock compositions. Additionally, the extreme plastic deformation during ShAPE enables the extrusion of billets with a high Si content that are too brittle for processing by conventional extrusion. By using 100% post-consumer shedder scrap as feedstock, ShAPE has the potential to slash embodied energy and carbon in extruded components by >80% compared to the conventional extrusion of primary aluminum alloys.

## ShAPE FOR RECYCLING

Unlike other high-shear extrusion processes such as equal channel angular extrusion (ECAE) that have limited scalability[7], ShAPE is in the process of being scaled to the industrial level and produces hollow and solid profiles of a variety of shapes including noncircular and multicell profiles. In 2016, Bond Technologies (Elkhart, Indiana) designed and manufactured the first purpose-built ShAPE machine for PNNL. In December 2023, Bond delivered a larger ShAPE 2 machine to PNNL capable of a ram force of 1350 kN, a torque of 12,000 N·m, and a capacity for extruding billets with diameters up to 75 mm. Although small compared to industrial-scale machinery, ShAPE 2 gives PNNL the ability to research process parameters important to scaling such as the ram force, spindle torque, and motor power. ShAPE has been applied to many materials including aluminum alloys, titanium alloys, high entropy alloys, polymers, oxide dispersion strengthened steels, electrical conductors, and thermoelectrics. A schematic of the process is shown in Fig. 1. ShAPE is also flexible to feedstock and has been used to extrude castings, powders, flakes, foils, and chips directly[8]. This flexibility in feedstock material and form factor positions ShAPE to be a promising technology for extruding mixed post-consumer Al scrap[9].

ShAPE has several additional benefits over conventional extrusion that are not specifically related to recycling. One is that most aluminum alloys, such as 2024, 6061, and 7075, can be extruded by ShAPE without subjecting the feedstock ingots to a homogenization heat treatment[10]. Homogenization is typically a time- and energy-intensive treatment (up to 18 hours at 450°C for 7075), and avoiding it can reduce energy, cost, and carbon emissions. Other advantages include precise control of the die temperature through the modulation of the rotational speed and improved materials properties through second-phase particle refinement and dispersion. These benefits make ShAPE a promising technique for manufacturing semifinished components from post-consumer aluminum alloy scrap.

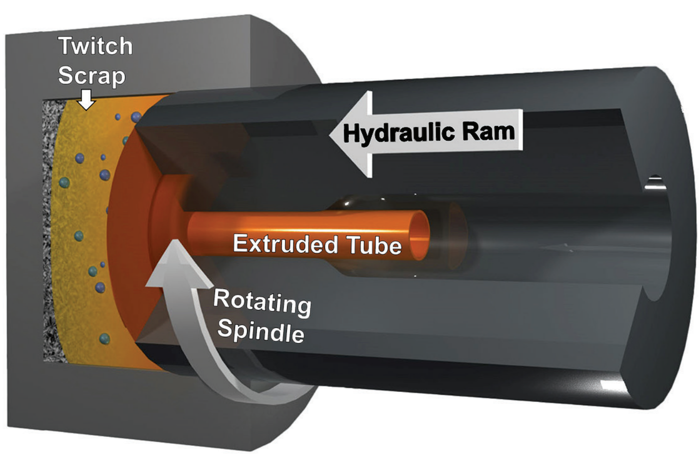



**Fig. 1 —** Schematic of ShAPE for indirect extrusion of seamless tubing with a floating mandrel. Image courtesy of Nathan Johnson/PNNL.

**Fig. 2 —** Left to right: Mixed Twitch Al alloy scrap supplied by Pacific Steel and Recycling; four Al alloy ShAPE-extruded tubes: a 1″ diameter tube, a multicell extrusion, a square tube, a clear anodized tube; and a blue anodized tube made with Twitch scrap.

## CASE STUDY: ShAPE RECYCLING OF MIXED TWITCH SCRAP

PNNL has performed a study on the recycling of 100% post-consumer scrap using ShAPE as part of the LightMAT Seedling Program within the U.S. DOE Vehicle Technologies Office. The scrap type of interest was mixed Twitch supplied by Pacific Steel and Recycling. Twitch is shredded scrap from automotive scrapyards, separated using a density flotation method. According to ISRI specifications, it must not contain more than 1% free zinc, 1% free magnesium, and 1% analytical iron[6]. Sometimes the Twitch scrap is separated further into cast and wrought alloys, but this study used mixed Twitch, which is a combination of both. Being a mix of wrought and cast scrap, there is a high content of several alloying elements, and this scrap stream cannot be made into any standard wrought aluminum alloy composition without extensive dilution with primary aluminum. The composition of extrusion billets cast from Twitch scrap was analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) and is summarized in Table 1, which compares it with the compositions of three common aluminum alloys.

The Twitch was first melted in its as-received condition and cast into cylindrical ingots with a diameter of 38 mm and a length of 178 mm by Eck Industries. These castings were then machined into extrusion billets with an outer diameter of 32 mm, an inner diameter of 10 mm, and a length of

## TABLE 1 – TWITCH REMELT COMPOSITION MEASURED USING ICP-MS, WT%

| Alloy | Cu | Fe | Mg | Mn | Si | Zn | Others | Al |
|---|---|---|---|---|---|---|---|---|
| Twitch | 1.48 | 0.56 | 0.88 | 0.20 | 4.56 | 0.48 | 3.5 | 88.3 |
| 6063 | <0.1 | <0.35 | 0.7 | <0.1 | 0.4 | <0.1 | <0.15 | bal. |
| 6061 | 0.3 | <0.7 | 1.0 | <0.15 | 0.6 | <0.25 | <0.15 | bal. |
| 6082 | <0.1 | <0.5 | 0.9 | 0.7 | 1.0 | <0.2 | <0.15 | bal. |

*Note: The nominal compositions of three commercial 6xxx-series Al alloys are given for comparison.*

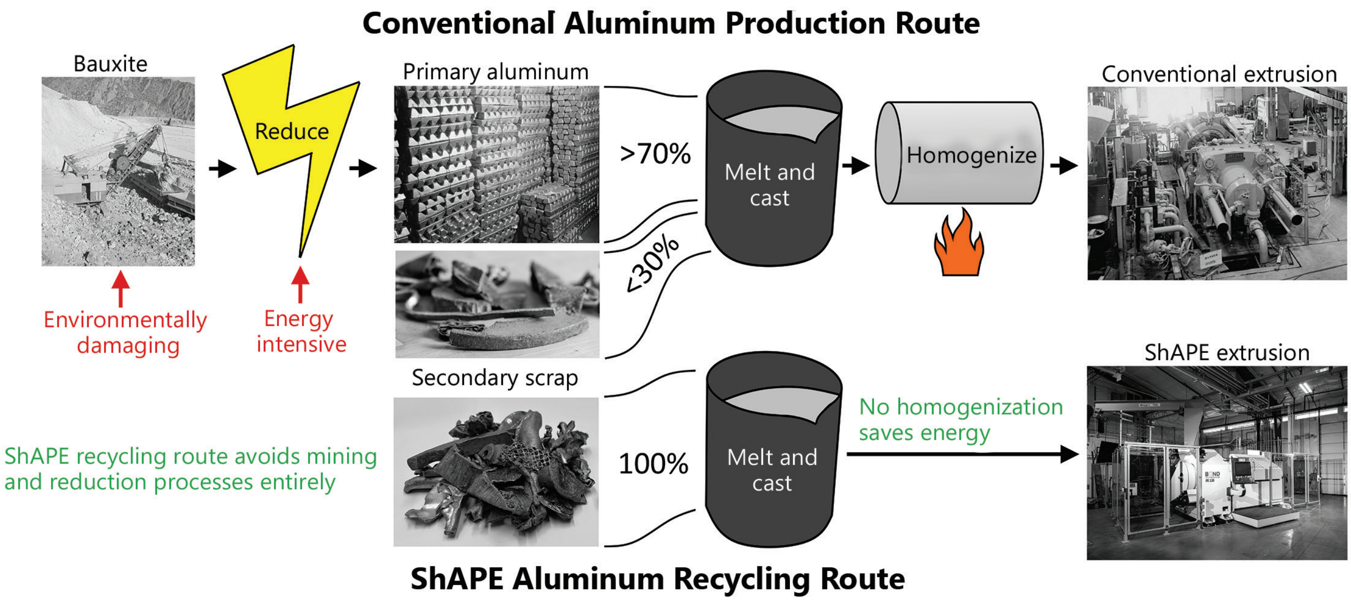



**Fig. 3 —** Flowchart of the conventional aluminum production route versus the ShAPE recycling route. Images courtesy of the Library of Congress and Andrea Starr/PNNL.

102 mm. To test the ability of ShAPE to refine second phases, no homogenization step was performed on the billets prior to extrusion. Billets were extruded using ShAPE into seamless tubing with outer and inner diameters of 12 and 10 mm, respectively (wall thickness: 1 mm), with a length of about 2 m (Fig. 2). The extrusion ratio was 20, the extrudate velocity was 7.2 m/min, the die rotation rate was 190 RPM, and the steady-state die temperature (measured using a thermocouple welded to the die face) was 520°C. Tubing was water-quenched immediately after exiting the die; then, specimens underwent a peak aging treatment at 180°C for 8 hours. A flowchart of the ShAPE aluminum recycling route compared to conventional extrusion is shown in Fig. 3.

The microstructures were observed using backscatter scanning electron microscopy (SEM) and are shown in Fig. 4. ShAPE acted to refine the structure, where the light-colored needle-shaped particles in the as-cast material (which were identified using electron dispersive spectroscopy to be the deleterious β-Al5(Fe,Mn)Si phase[9]) have been broken up into smaller, blocky particles in the ShAPE material. The refinement and morphology change from needle-shaped to blocky is expected to reduce the stress concentrations and increase the ductility of the ShAPE-processed material.

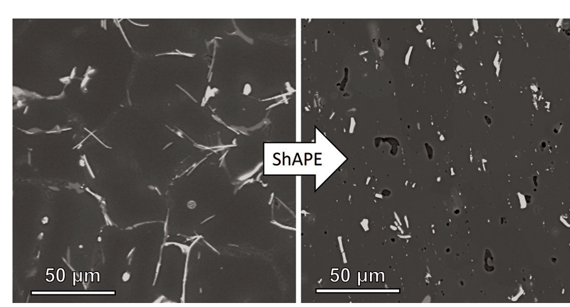



**Fig. 4 —** SEM backscatter images of the as-cast Twitch billet (left) and ShAPE-processed Twitch tube (right).

The ShAPE-processed tubes from unhomogenized billets were then independently tensile-tested by Westmoreland Testing and Research Inc. according to ASTM standards E8-22 and B557-15 on four replicates[11]. Remarkably, the yield and ultimate tensile strengths of the 100% Twitch

## TABLE 2 – MECHANICAL PROPERTIES OF ShAPE-PROCESSED TWITCH SCRAP COMPARED TO THE ASTM MINIMUM STANDARD FOR COMMON 6000-SERIES ALUMINUM ALLOYS

| Specimen | Yield strength, MPa | UTS, MPa | Strain at break, % |
|---|---|---|---|
| ShAPE-Twitch | 284 ± 6 | 356 ± 4 | 10.4 ± 0.8 |
| 6063-T6 Min. | 172 | 207 | 8 |
| 6061-T6 Min. | 241 | 262 | 8 |
| 6082-T6 Min. | 250 | 295 | 8 |

*Note: The yield strength was determined with the 0.2% offset method. The error represents the standard deviation of the four specimens tested.*

alloy exceeded those of conventional 6061 while still retaining reasonable ductility. These tensile properties are listed in Table 2.

## GOING FORWARD

This work represents the first steps toward discovering the potential for ShAPE to reach deep into the aluminum scrap stream and upcycle low-value scrap directly into high-value wrought products without adding primary aluminum. One promising application of ShAPE with aluminum scrap is for the building and construction (B&C) industry, where decarbonizing the built environment is a major objective. The ability of ShAPE to extrude post-consumer scrap has the potential to be a game-changing technology in light of tightening government regulations, commitments to corporate sustainability goals, and increasing incentives for reducing embodied energy and lifecycle $CO_2$ emissions[12]. Another advantage for the B&C industry is that most components are finished with surface coatings like anodization, powder coating, or polyvinylidene fluoride (PVDF), which can mitigate the lower corrosion resistance of Twitch-based alloys caused by high Cu and Si contents[13]. ShAPE of post-consumer scrap also offers the potential for reduced product cost since the price of scrap is a fraction of the cost of primary aluminum alloys. With >50% of the global aluminum extrusion market consumed by the B&C industry and the majority of B&C alloys being 6061 and 6063, there is a sizable opportunity for ShAPE of post-consumer scrap to meet performance requirements while simultaneously offering a cheaper and more sustainable alternative[14].

Another application that has the potential for high impact is the automotive industry. As more aluminum is used in vehicles, the amount of scrap being recycled from these vehicles will also increase. This "scrap wave" has the potential to meet up to 80% of the U.S. automotive industry needs for aluminum by 2050, if manufacturing approaches can be identified that can convert near 100% scrap streams to high-performance automotive components[15]. It is expected that vehicles will continue to increase in aluminum content in the future, either to improve fuel efficiency in gas/diesel vehicles or to increase range in electric vehicles. In this application, the requirements for formability, corrosion resistance, and strength can be more stringent than those in the B&C industry. The solution to this challenge is to further diversify scrap sourcing to create compositions that are lower in tramp element content and are more similar to existing alloy specifications. Twitch would continue to be an inexpensive and plentiful scrap source for this application, but the high Si and Cu contents would likely cause issues with formability and corrosion resistance. One solution that industry is exploring is sorting Twitch into wrought and cast fractions. Although sorting is imperfect, an 80 to 90% efficiency yields a composition considerably lower in Si and Cu compared to mixed Twitch. The wrought fraction can be combined with a variety of other scrap streams such as used beverage cans, conductors, building demolition, and cuttings/trimmings from industrial extrusion and stamping processes. These scrap streams could then be blended to create compositions similar to on-spec alloys for the automotive industry as a replacement with sharply reduced embodied energy and carbon.

PNNL will continue to push the envelope for ShAPE of scrap alloys, reaching into sectors such as B&C, automotive, aerospace, marine, electrical transmission, and feedstock for additive manufacturing. The novel ShAPE machinery constructed by Bond Technologies and PNNL's development of scrap alloys, process know-how, tooling designs, and post-processing techniques are a promising new approach for sustainable metals manufacturing. **~AM&P**

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## GET ENGAGED, GET INVOLVED, GET CONNECTED

The ASM Sustainable Materials Engineering Committee meets regularly to connect and communicate about their shared interest in green materials and processes. For more information, contact staff liaison Scott Henry, scott.henry@asminternational.org.

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