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PNNL-33766

Shear Assisted Processing and Extrusion (ShAPE) of Lightweight Automotive Components (CRADA 418)

Final Technical Report

January 2023

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Brandon Scott Taysom
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U.S. DEPARTMENT OF ENERGY

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Richland, Washington 99354

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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date: January 2023

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to Agreement: Pacific Northwest National Laboratory and Magna Services of America

CRADA number: 418

CRADA Title: Shear Assisted Processing and Extrusion (ShAPE) of Lightweight Automotive Components

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DOE Program Office: Vehicle Technologies Office (VTO) LightMAT Consortium

Joint Work Statement Funding Table showing DOE funding commitment:

DOE Funded Portion: $1,000,000

Industry Funded Portion: >$2,000,000

Executive Summary

Shear Assisted Processing and Extrusion (ShAPE) was developed to manufacture non-circular multicell profiles from secondary aluminum. This was accomplished by integrating a porthole die approach within the rotating ShAPE process. Complexity of the profile geometry was deliberately advanced over the course of the project from round to square, to asymmetric trapezoidal, to two-cell asymmetric trapezoidal. Aluminum alloy 6063 in the form of briquettes (compacted shreddings and engineered machining chips) and castings from pre-consumer industrial scrap were utilized as the feedstock. Tensile properties were shown to exceed the ASTM minimum standard and ASM typical values with the best results reaching yield strength = 247 ± 10 MPa, ultimate tensile strength = 271 ± 10 MPa, and uniform elongation = 16.5 ± 2.4%. These values were achieved for porthole extrusion using unhomogenized castings made from 100% aluminum 6063 industrial scrap. The ability to extrude unhomogenized billet was made possible by in situ conversion of plate-like β-type Fe-rich intermetallics to more extrudable needle-like α-type which is not possible with conventional extrusion. By eliminating the need to dilute iron with primary aluminum during the recycling process, savings of >90% on lifecycle carbon footprint and >50% on embedded energy could ultimately result in lower cost, more environmentally friendly, automotive components.

Research Results

Objective

The overarching objective of this project was to demonstrate the feasibility of using Shear Assisted Processing and Extrusion (ShAPE) to manufacture multicell extrusions from secondary aluminum. This report highlights progress toward this objective.

Introduction

Automotive components made from 100% secondary aluminum offer >50% energy savings and >90% CO_2 savings during the manufacturing process compared to conventional extrusion. Use of secondary Al as the feedstock is not only environmentally friendly but can significantly reduce the cost of components. This is because the need to dilute Fe with primary Al can be eliminated [1-2] thus removing the energy, carbon, and cost associated with production of primary aluminum. Additionally, lightweight automotive components made from Al alloys offer 25% weight savings compared to state-of-the-art high-strength steel. As a result, steel components are being targeted for replacement by Al where feasible. To improve recyclability, this Cooperative Research and Development Agreement (CRADA) between the Pacific Northwest National Laboratory (PNNL) and Magna Services of America (Magna) aimed at developing ShAPE to demonstrate the potential for converting Al industrial scrap directly into sub-scale automotive components. Al electric vehicle (EV) battery structures provide one possible insertion opportunity based on equal, or improved performance, at a reduced cost as compared to conventional extrusions. The potential cost reduction and environmental benefits of using feedstock comprised of 100% secondary Al are well established [1-4]. Use of secondary scrap without the addition of primary Al, however, has not developed into an industry process due to fundamental material challenges associated with intermetallic dispersion [5] and uniform microstructure [6]. These process limitations have been overcome using severe plastic deformation (SPD) techniques [7], such as equal channel angular pressing (ECAP) [8]. Although successful from a scientific standpoint, ECAP and other SPD processes are not scalable to an industrial level. ShAPE combines the microstructural advantages of SPD, with the scalability of a conventional extrusion process to offer a unique technology for converting Al secondary scrap directly into automotive components while meeting industry standard property requirements.

Approach

Unlike conventional extrusion where the die is pressed against a pre-heated billet using a strictly linear motion, ShAPE superimposes a rotational shear force by spinning the die. The ShAPE process is described in detail elsewhere [9-12]. The basic operation is shown in Fig. 1a and briefly described here for convenience. Contact between the billet and rotating die generates frictional heating at the die/billet interface and within the upper layer of the billet due to plastic deformation. The extent of heat generation and depth of the deformation zone is controlled by regulating rotational speed, temperature, and ram speed. As a result, the heat required to soften the material is entirely provided by the process, and billet pre-heating in a separate furnace is not required. As the temperature increases, material plastically flows inward toward the extrusion orifice through spiral grooves machined into the die face. Upon exiting the grooves, the flow streams consolidate prior to entering the extrusion orifice where the material then flows between the mandrel and weld chamber to form a tube using a floating mandrel (Fig 1a) or porthole die (Fig. 1b) configuration. Figure 2 shows PNNL’s first-of-its-kind ShAPE machine manufactured by Bond Technologies in Elkhart, Indiana, USA, and is the manufacturing platform utilized for this project.

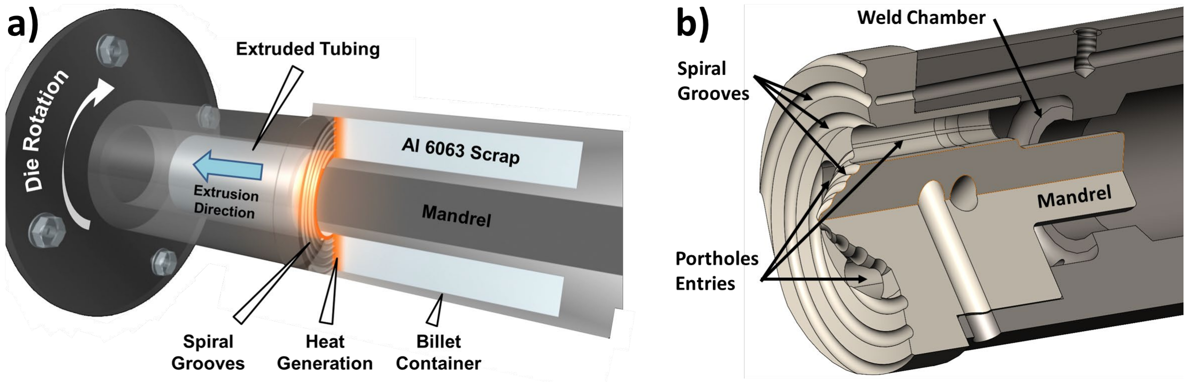


Figure 1. a) Schematic of Shear Assisted Processing and Extrusion (ShAPE) technology in a floating mandrel configuration and b) porthole die configuration. Source: PNNL

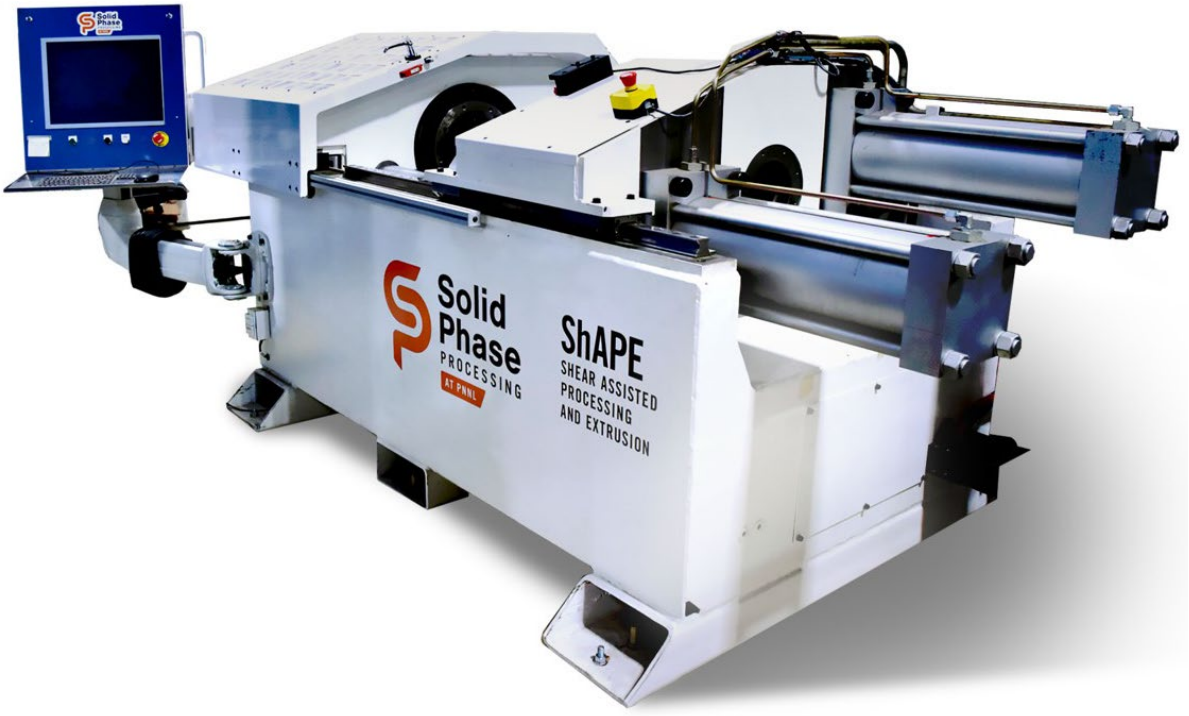


Figure 2. First-of-its-kind ShAPE machine installed in PNNL's Solid Phase Processing Laboratory. Source: PNNL

Feedstock Materials

Two Al 6063 feedstock form factors were investigated over the course of this project: briquettes and castings. Briquettes consisted of particulate compacted into billets with the material source being engineered chips and shredded scrap. Castings consisted of re-melted industrial scrap sourced from one of Magna's manufacturing facilities. Briquettes contained Al 6063 in the T6 condition while castings were supplied in the as-cast unhomogenized condition. A small number of extrusion trials were performed on Al 6061 and Al 6082 castings to satisfy the project team that the ShAPE tooling and process parameters were robust to other 6XXX alloys. Figure 3 shows examples Al 6063 billets fabricated in cast (Fig. 3a) and briquette (Fig. 3b) form.

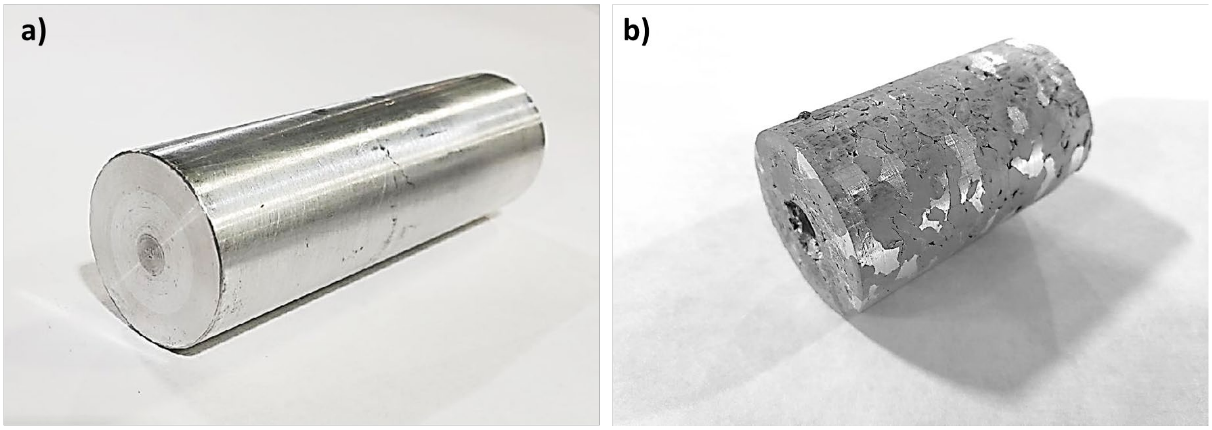


Figure 3. a) Cast billet prepared from 100% industrial scrap for porthole extrusion. Briquette prepared from shreddings of 100% industrial scrap for floating mandrel extrusion. Source: PNNL.

Process Development

Approximately 400 extrusions were performed over the course of this project to develop process parameters and tooling configurations that achieved adequate extrusion speed, surface finish, and mechanical properties. Figure 4 shows the progression of extrusion quality over the life of the project as the project team discovered the influence of tooling features and process conditions. Figure 4a represents early trials with low extrusion speed and lack of consolidation. Figures 4b and 4c represent intermediate development with full consolidation and progressively faster extrusion speeds. Figure 4c represents final development with fully optimized tooling and process parameters for Al 6063 billet comprised of 100% secondary scrap.

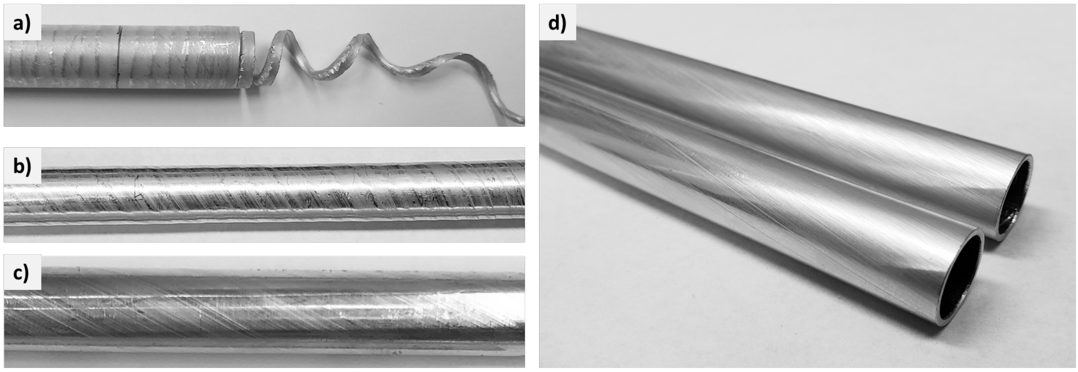
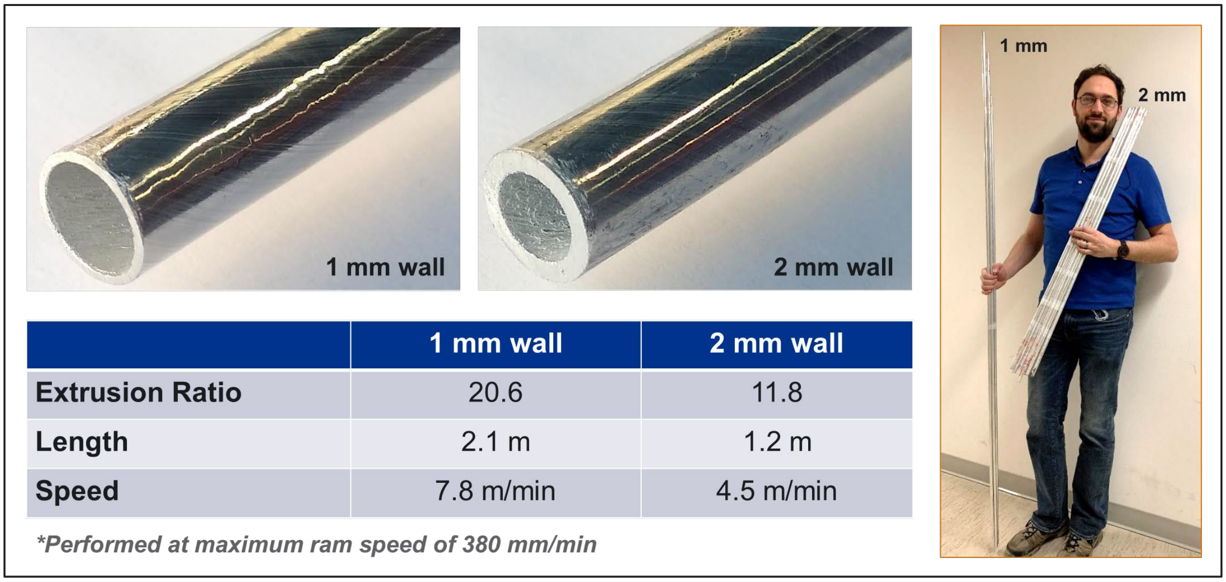


Figure 4. a) Early trial showing slow speed and lack of consolidation. b) Intermediate trial showing full consolidation but slow speed and uneven surface. c) Intermediate trial showing improved surface finish and higher speed. d) Late trial showing excellent surface quality due to optimized process parameters and tooling features. Source: PNNL.

This project began using the floating mandrel approach in Figure 1 to manufacture round hollow tubing. Hundreds of extrusions with 12 mm outer diameter (OD) with 1 mm and 2 mm wall thickness were fabricated as shown in Figure 5 and 6 with an extrusion ratio of 20.6 and 11.8 respectively. This resulted in an extrudate velocities of 7.8 m/min and 4.5 m/min at a ram speed of 380 mm/min (maximum ram speed of the ShAPE machine). Prior to this project, the maximum extrudate velocity achieved by PNNL for the same extrusion ratio and tube dimensions was just 0.078 m/min. Thus, extrusion speed was increased by approximately 100 times over the course of this project. The die configurations and process parameters developed on this project are now the foundation for all aluminum ShAPE projects now underway at PNNL and are fully described in the referenced literature.



	1 mm wall	2 mm wall
Extrusion Ratio	20.6	11.8
Length	2.1 m	1.2 m
Speed	7.8 m/min	4.5 m/min

Performed at maximum ram speed of 380 mm/min

Figure 5. Extrusion speed achieved for 12 mm OD tubing with 1 mm and 2 mm wall thickness. Source: PNNL.

Figure 6. Bundle of ShAPE extruded Al 6063 tubing with 12 mm OD and 2 mm wall thickness. Source: PNNL.

Mechanical Properties

Table 1 shows tensile properties for four different feedstocks that were investigated during this project. The research for each case is fully documented in the associated references. In all cases, the reported properties are in the T6 condition. The last two rows provide the ASTM Minimum Standard and ASM Typical Values for comparison. All tensile tests were performed per ASTM E8 and ASTM B557-15 by Magna. Results for feedstocks comprised of 100% industrial scrap compare favorably to the standard values for primary aluminum.

Table 1. Tensile properties for four different Al 6063 feedstocks investigated during this project compared to the ASTM Minimum Standard and ASM Typical Values for primary aluminum.

Al 6063 Feedtock	Method	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
Wrought T5 [11]	Floating Mandrel	198 ± 16	243 ± 14	11.0 ± 6.9
Chipped Briquette from 100% Industrial Scrap [15]	Floating Mandrel	204 ± 9	231 ± 8	17
Unhomogenized Casting from 100% Industrial Scrap [16]	Porthole Die	247 ± 10	271 ± 10	16.5 ± 2.4
Unhomogenized Casting from 100% Industrial Scrap with 0.34 wt% Fe [17]	Floating Mandrel	206 ± 5	238 ± 5	16.3 ± 1.1
ASTM Minimum Standard for Primary Aluminum [13]	N/A	170	205	8*
ASM Typical Values for Primary Aluminum [14]	N/A	214	241	12*

*Note: The standard values are for total elongation. The values reported for ShAPE are for uniform elongation suggesting that ShAPE process material has higher ductility than conventionally extruded material. This is discussed in the referenced publications.

Microstructure

The microstructure of ShAPE extruded Al 6063 is generally characterized by highly refined and equiaxed grain structure. Figure 7 shows grain structure (Fig. 7a) by Scanning Electron Microscopy (SEM) for wrought Al 6063-T5 billets utilized as the feedstock in [11]. As an already extruded product, the microstructure of the wrought billet has already been refined to an average grain size of 66 µm from a cast microstructure by conventional extrusion. Figs. 7 b-d show the ShAPE extruded microstructure, also in T5, formed at various extrusion speeds. The grain structure is further refined by ShAPE where an average grain size of 15-20 µm is observed.

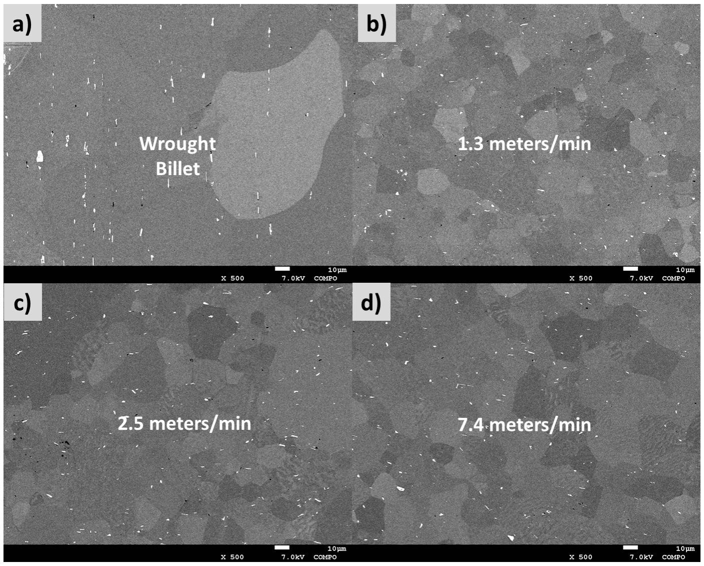


Figure 7. a) Grain structure of wrought Al 6063-T5 billet. b-d) Grain structure of ShAPE extruded material at different extrusion speeds. Source: PNNL.

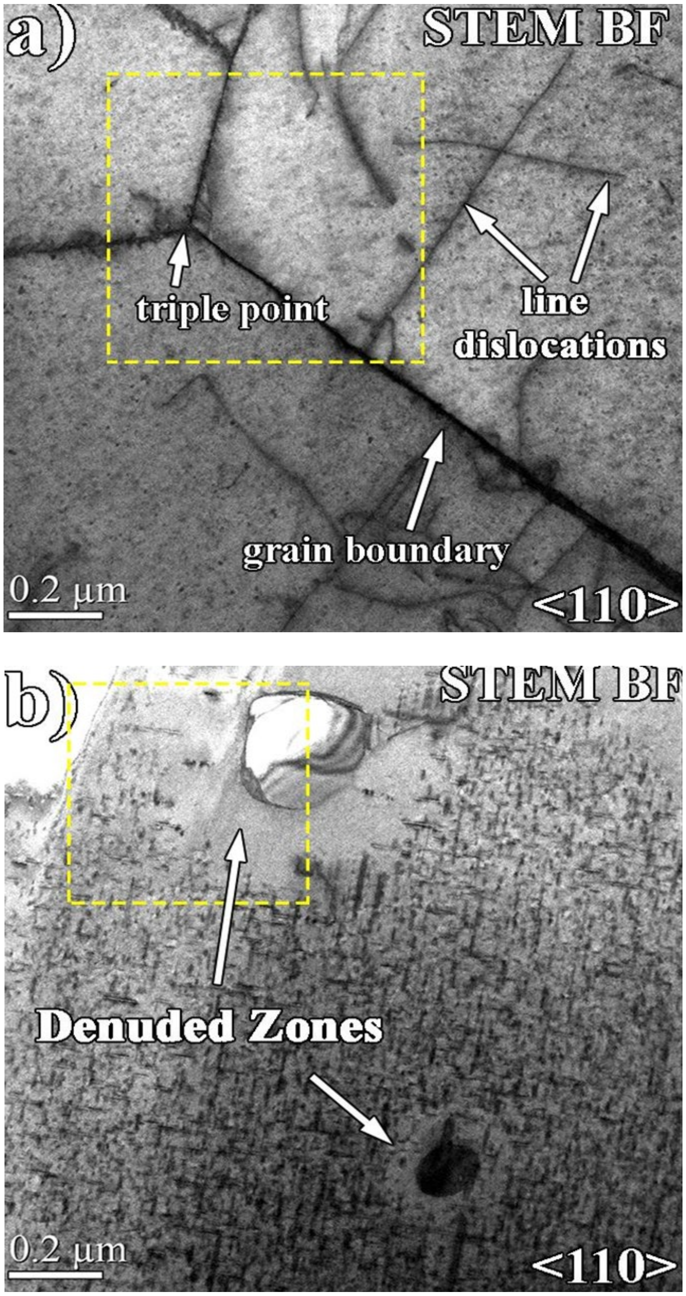


Figure 8. a) TEM data of Al 6063 in the as-extruded condition after ShAPE processing. Billet was wrought Al 6063-T5. b) TEM data of Al 6063 heat treated to the T5 condition after ShAPE processing. Billet was wrought Al 6063-T5. Source: PNNL

Figure 8 shows data from Transmission Electron Microscopy (TEM) for wrought Al 6063-T5 billets extruded using the ShAPE process. Figure 8a show that β-type precipitates are not observed in the microstructure indicating that solutionizing occurs during ShAPE. Figure 8b shows that significant β’ and β’’ precipitates are observed after T5 heat treatment, which are the primary strengthening precipitates in Al 6063. Further scientific detail is found in [11]. In situ solutionization of β-phase was also achieved during extrusion of unhomogenized as-cast Al 6063 billet from 100% industrial scrap suggesting the homogenization is not needed prior to ShAPE processing as described in [16].

It has also been demonstrated that ShAPE is capable of processing unhomogenized Al 6063 castings made from industrial scrap through extensive grain refinement and breakdown and dispersion of Fe-enriched and Mg-enriched second phases, as fully described in [17]. Floating mandrel extrusions were performed where the Al 6063 castings were spiked to 0.34 wt% Fe (upper composition limit for Al 6063) and the melt was intentionally unskimmed to purposely generate a somewhat ‘dirty’ feedstock. Figure 9 shows low magnification (a)-(c) and high magnification (d)-(f) SEM-backscatter electron (BSE) images of microstructures observed in the unhomogenized cast billets (a and d), transverse ShAPE extrusion (b and e), and longitudinal ShAPE extrusion (c and f). This analysis shows the extent of grain refinement following ShAPE processing, quantified in Table 2. The extruded grain structure is highly equiaxed with similar grain size in the longitudinal and transverse direction as shown in Table 2.

Table 2. Grain size analysis with Feret diameter reported as an area-weighted mean. Extrusions fabricated from Al 6063 industrial scrap spiked to 0.34 wt% Fe and unskimmed.

Sample	Maximum Feret Diameter (µm)	Standard Deviation (µm)
Unhomogenized Cast Billet	343	137
ShAPE Transverse	73	25
ShAPE Longitudinal	62	121

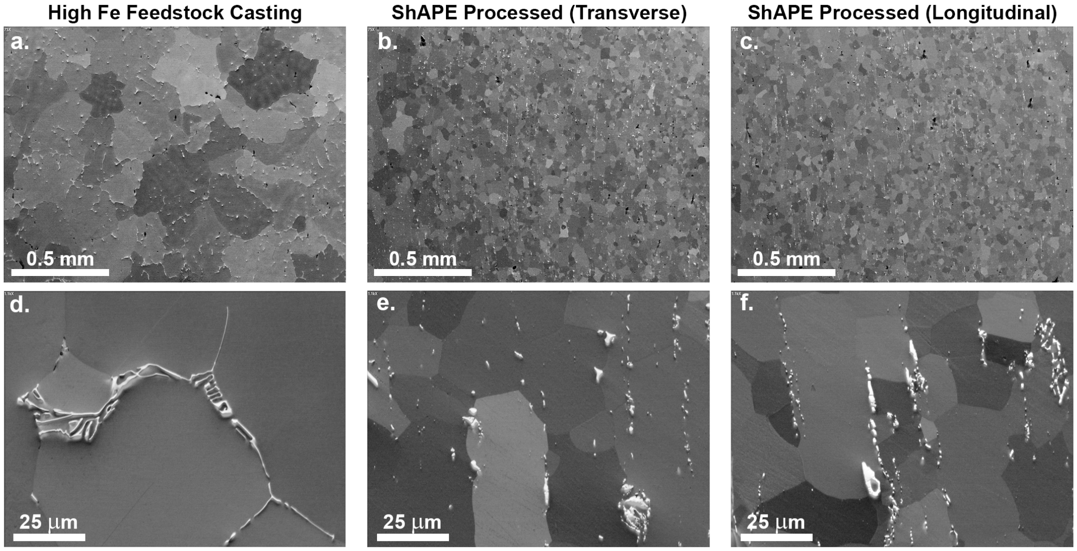


Figure 9. SEM-BSE images of the unhomogenized cast billets made from Al 6063 industrial scrap spiked to 0.34 wt% Fe and unskimmed. (a and d), transverse ShAPE extrusion (b and e), and longitudinal ShAPE extrusion (c and f). Source: PNNL.

Figure 10 depicts Energy Dispersive Spectroscopy (EDS) maps showing the presence of FeAlSi-enriched IMCs along grain boundaries in the unhomogenized cast billets (a). Figures 10(b-c) show that these Fe-enriched IMCs have been significantly refined and evenly dispersed throughout the Al matrix during ShAPE extrusion. Following ShAPE processing, IMCs exhibit a reduced propensity to decorate grain boundaries, and exhibit a more random distribution, and appear both inter- and intragranularly. This is corroborated by comparing the bright second phases in Fig. 10(d) with (e-f). Figure 10b shows MgSiO-enriched IMCs which result from the billet casting process where the melt was not skimmed or degassed. Note, the magnification of (b) was increased by a factor of 10 to clearly visualize this phase for comparison to the cast material. The size of the MgSiO cast defects were significantly reduced during ShAPE which is advantageous since large defects can have a deleterious effect on mechanical properties.

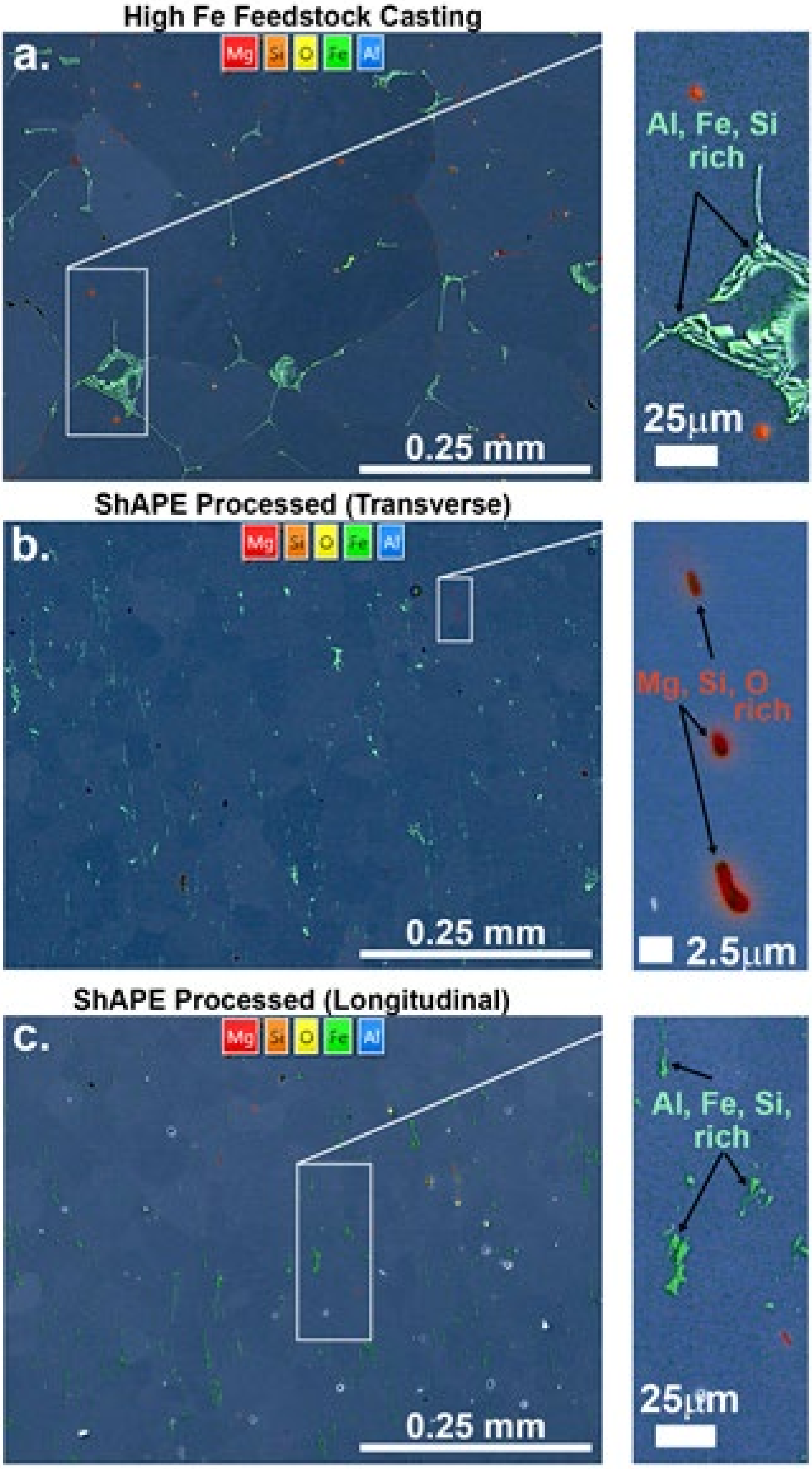


Figure 10. EDS analysis of unhomogenized cast billets (a), transverse ShAPE extrusion (b), and longitudinal ShAPE extrusion (c). *Note the callout presented in (b) is a 10X increase in magnification to better show the refined MgSiO-enriched phase. Source: PNNL.

Multicell Profile

A primary objective of this project was to demonstrate that ShAPE can extrude industrial scrap with non-circular multicell profiles. This was critical for showing the potential for ShAPE to manufacture structure profiles of interest to Magna. Figure 11 shows (a) the extruded profiles manufactured using a porthole die configuration, (b) schematic of a porthole die integrated with a rotating billet, (c) porthole die assembly with surface features to assist material flow, and (d) back side of the porthole die head showing port exits and square mandrel.

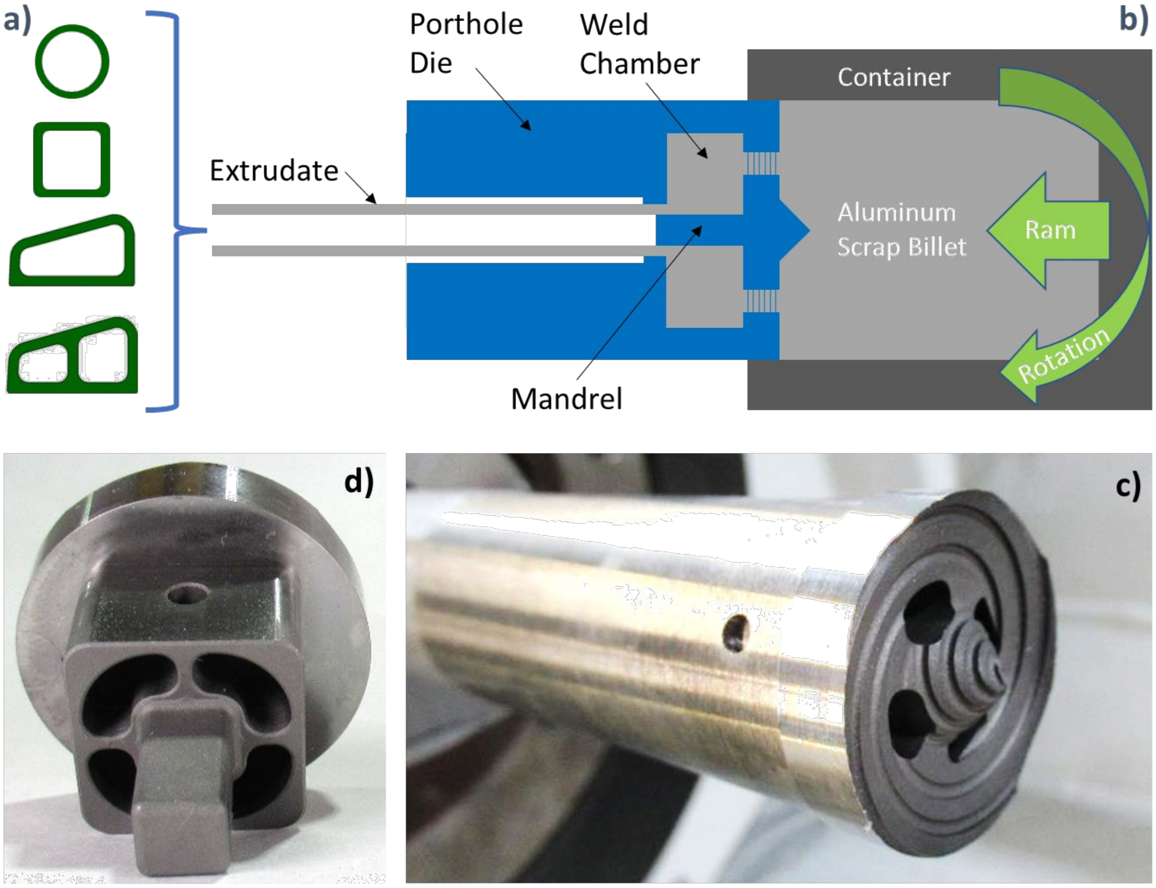


Figure 11. a) Extruded profiles manufactured using a porthole die integrated with the ShAPE process. (b) Schematic of porthole die integrated with a rotating billet. (c) Porthole die assembly with surface features to assist material flow. (d) Back side of porthole die head showing port exits and square mandrel. Source: PNNL

To demonstrate extrusion of industrial scrap by ShAPE, Magna provided PNNL with cast billets comprised of 100% industrial scrap Al 6063 collected from one of Magna's manufacturing facilities. Cast billets were supplied to PNNL in the unhomogenized condition. PNNL extruded these cast billets using porthole tooling designed by PNNL (round and square) and Magna (trapezoidal and 2-cell trapezoidal) with all tooling fabricated by Magna. Multiple extrusions were performed for the process conditions shown in Table 3. Water quenching was incorporated near the die exist to achieve "press quenching" as is typical for industry. The circular, square, trapezoidal, and two-cell trapezoidal profiles had a nominally 2 mm wall thickness with the characteristic diameter of each profile being: circular, 12.7 mm; square, 13.9 mm; trapezoidal and two-cell trapezoidal, 18.1 mm.

After extrusion, 150 mm long sections were cut from the round tubes and artificially aged at 177°C for eight hours to achieve a T6 temper. No solution heat-treating was performed prior to artificial aging to discover if press quenching was achieved. The 150 mm long specimens were fitted with tapered plugs on each end per ASTM E8 and pulled at Magna on a Instron 8802 load frame with a 25-kN load cell at a rate of 0.02 mm/s and a 25-mm mechanical extensometer for measuring displacement of the gauge length.

Table 3. Process Parameters for ShAPE extrusion of Al 6063 Industrial Scrap using Porthole Dies.

Extrudate Profile	Billet Diameter (mm)	Extrusion Ratio (ER)	Die Rotation (rpm)	Die Face Temperature (°C)	Ram Force (kN)	Ram Speed (mm/min)
Round	31.8	11.4	55	460	610	120
Square	31.8	11.0	40	490	720	120
Trapezoid	38.1	9.1	30	510	390	10
2-Cell Trapezoid	38.1	7.9	40	500	370	10

Extrudates shown in Figure 12 were approximately 1 meter long from 10 cm long billets. Round extrusions were investigated initially to (1) solve engineering challenges associated with integrating a rotating billet into the ShAPE process and (2) demonstrate that aluminum could be separated into ports and recombined while rotating the billet. The circular profile and surface appearance for round tubing are shown in Figure 12(a). The weld chamber and mandrel were then modified to produce the square profile shown in Figure 12(b). Next, the port configuration, mandrel geometry, and weld chamber were redesigned by Magna to form an asymmetric trapezoidal profile. HyperXtrude simulations were performed by Magna to check that all regions of the extrudate had nominally the same velocity to promote weld seam closure and avoid curling. The trapezoidal profile and surface appearance are shown in Figure 12(c). Finally, the trapezoidal mandrel was modified by Magna to form an internal web, thereby generating the two-cell profile shown in Figure 12(d). With systematically increasing complexity, the ShAPE process has demonstrated the ability to extrude noncircular, asymmetric, multicellular profiles from Al 6063 industrial scrap. Thus, the ultimate objective of this project was achieved by demonstrating a multicell extrusion using the ShAPE process.

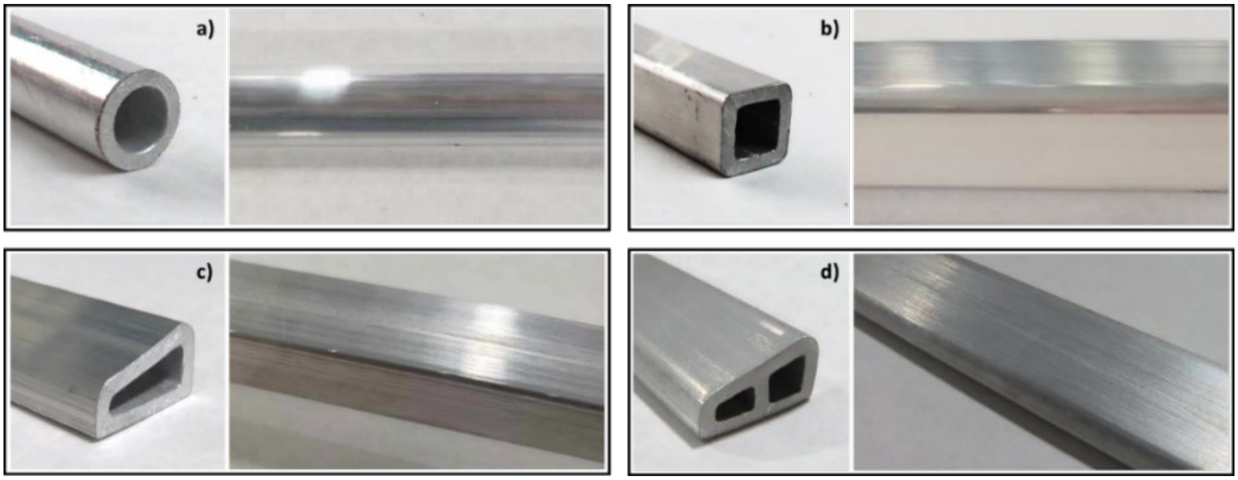


Figure 12. Extrusions made from Al 6063 industrial scrap by ShAPE using porthole die configurations producing (a) circular, (b) square, (c) trapezoidal, and (d) two-cell trapezoidal profiles. Source: PNNL

For all profiles, wall thickness varied by less than ±5% along the extrudate length, which is typical of conventional extrusion and within specification for Magna. Yield strength (246.9 ± 10.4 MPa), ultimate tensile strength (270.8 ± 9.6 MPa), and elongation (16.5 ± 2.4%) all exceeded industry standards [13,14] as shown in Table 4. Surface roughness was measured to be R_a = 4.93 μm ± 0.40 μm as the average of 40 lines scans per face on each of the four exterior surfaces of the trapezoidal profile.

Table 4. Tensile Properties of 2-mm Thick Round Tubing Extruded by ShAPE from Al 6063 Industrial Scrap Compared to ASTM [13] and ASM [14] Standards. Note: *Total Elongation

Property	ShAPE Al 6063 Scrap	T6 ASTM Min. [13]	T6 ASM Typ. [14]
Yield Strength (MPa)	247 ± 10	170	205
Ultimate Strength (MPa)	271 ± 10	214	241
Elongation (%)	16.5 ± 2.4	8	12

Table 4 shows that yield and ultimate strengths for ShAPE extruded Al 6063 are significantly higher than conventionally extruded 6063 in the T6 condition, per ASTM and ASM. This demonstrates that the Mg_2Si strengthening phase is driven into solution during extrusion and that press quenching was effective in minimizing Mg_2Si coarsening. Additionally, Al 6063 castings must by homogenized prior to conventional extrusion to convert plate-like Fe-rich β_c into more extrudable needle-like α_c [15]. With ShAPE, the $\beta_c \rightarrow \alpha_c$ conversion occurs during the extrusion process due to the combination of extreme shear deformation at elevated temperature [16]. This enables bypassing of the energy intensive homogenization heat treatment. This work validates that ShAPE can extrude 6063 casting made from 100% scrap with properties adequate for applications where conventionally extruded 6063 is a candidate.

A microstructural analysis of the trapezoidal profile in the as-extruded condition is presented in Figure 13, illustrating the microstructural refinement achieved for ShAPE extruded Al 6063 industrial scrap using a porthole die. The scanning electron microscope (SEM) secondary electron (SE) image montage presented in Fig 13(a) shows full consolidation free of macro-level voids or weld seam defects. Figs 13(b, c, e and g) show electron backscatter diffraction (EBSD) data collected midway through the wall thickness and Figs. 13(d and f) show data at the inner and outer surfaces of the profile, respectively. The microstructure is highly refined and equiaxed with average grain sizes statistically similar for each location. The average grain size for all locations was 6.7 μm with a standard deviation of 4.6 μm. Grain size examined through the wall thickness had no statistical variation. The inverse pole figures (IPF) shown are parallel to the extrusion axis (Z). Pole figure plots are shown for the {001} planes and illustrate texture development. Local texture depends on the location examined across the extrudate profile, which suggests deformation gradients exist within the workpiece during processing. SEM images from the entire SE montage were examined for evidence of incomplete weld seam fusion. This search revealed that all areas were fully recrystallized, and no weld seam defects were detected.

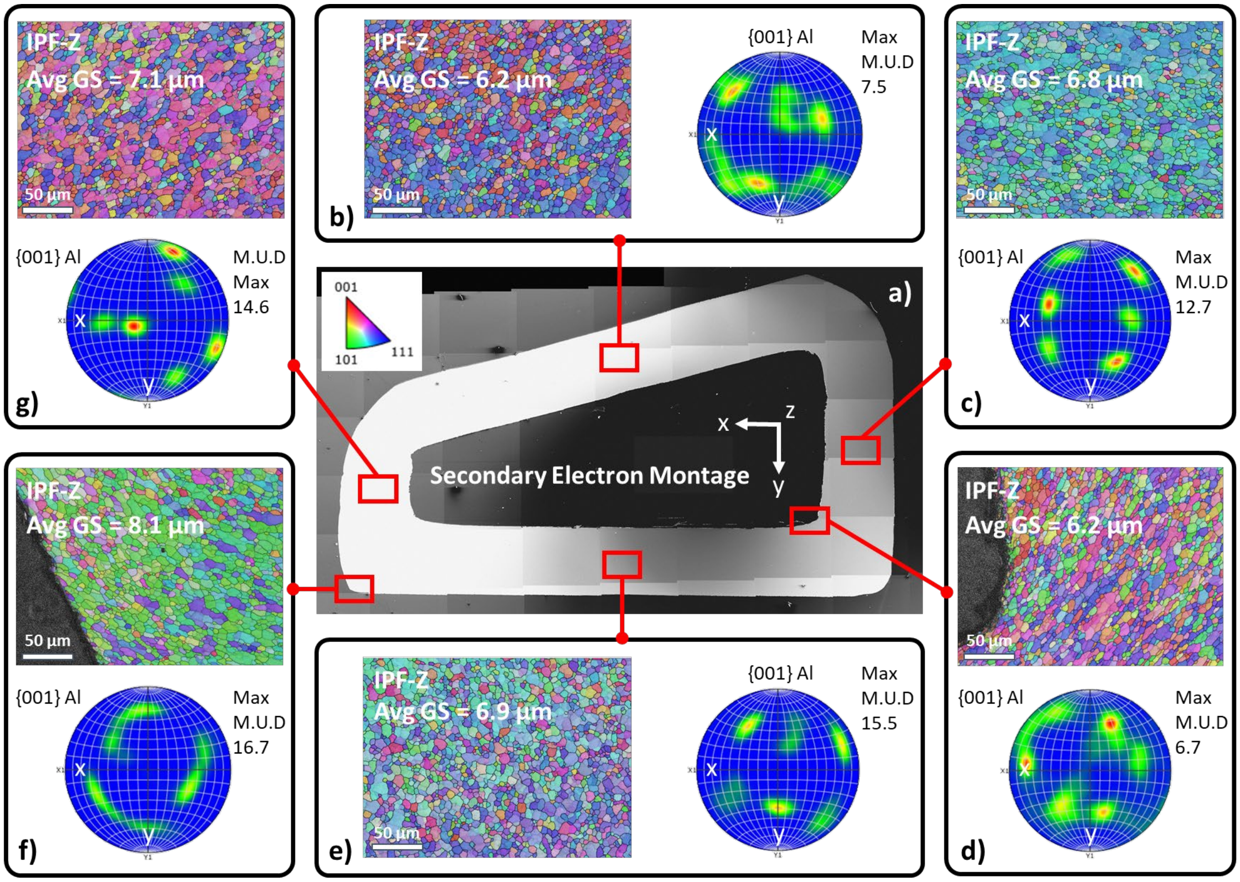


Figure 13. (a) SE image montage of a trapezoidal extrudate cross section in the as-extruded condition without voids or weld seam defects. (b-g) Microstructure at various locations showing highly refined and uniform grain size (GS) and crystallographic orientation indicating weak texture. Locations b, c, e, and g are at the expected weld seam location and show no bonding or texture defects. M.U.D. is multiple of uniform density. Source: PNNL

Conclusions

This project demonstrated the feasibility of using Shear Assisted Processing and Extrusion (ShAPE) to manufacture multicell extrusions from secondary aluminum. The following milestones were achieved over the course of the project.

- Increased ShAPE extrusion speed by 100 times compared to prior ShAPE research.
- Extruded non-circular, asymmetric, multicell trapezoidal profile using a porthole die integrated with the ShAPE technology.
- Extruded 100% secondary Al 6063 scrap from castings with tensile properties exceeding the ASTM minimum standard and ASM typical values.
- Extruded 100% secondary Al 6063 scrap from castings spiked to 0.34 wt% Fe with tensile properties exceeding the ASTM minimum standard and comparable to ASM typical values.
- Extruded 100% secondary Al 6063 scrap from briquettes with tensile properties exceeding the ASTM minimum standard and comparable to ASM typical values.
- Eliminated the need to dilute Fe with primary Al during recycling which reduces lifecycle carbon footprint by >90% and embedded energy by >50%.
- Eliminated the need for energy intensive billet homogenization after casting.
- Developed intellectual property for novel tooling, fixtures and processing by ShAPE.

Publications

1. Taysom, B. S., N. Overman, M. Olszta, Md. Reza-E-Rabby, T. Skszek, M. DiCiano, and S. Whalen, 2021, “Shear-assisted processing and extrusion of high-strength aluminum alloy 6063 tubing,” *International Journal of Machine Tools and Manufacture*, Vol. 169, Art. 103798.
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3. Whalen S., N. Overman, B.S. Taysom, Md. Reza-E-Rabby, T. Skszek, M. DiCiano, “Effect of High Iron Content on Direct Recycling of Unhomogenized Aluminum 6063 Scrap by Shear Assisted Processing and Extrusion,” *Materials and Design*, Under Review.
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