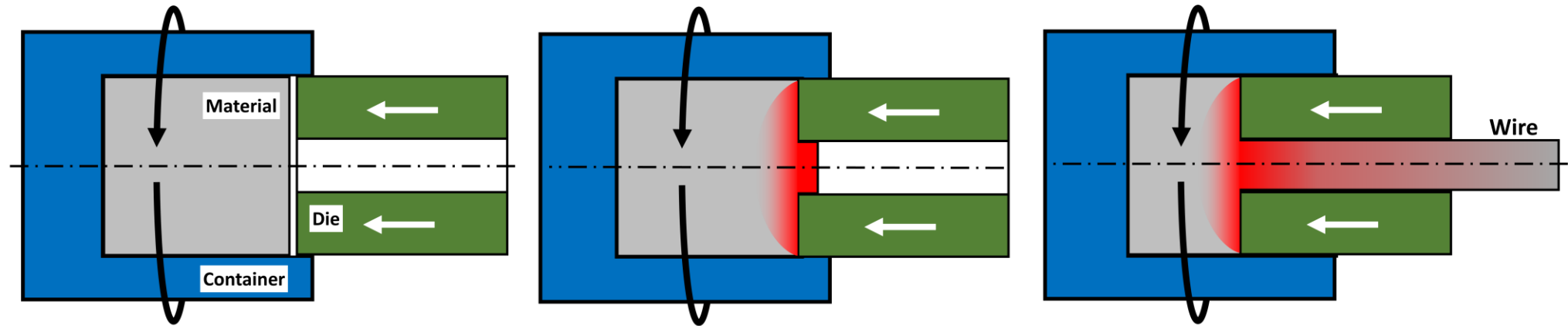


Friction Extrusion: An Emerging Solid-State Technique for Processing, Recycling, Upcycling and Mechanical Alloying of Aluminum Alloys

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D-21502 Geesthacht
Germany

Friction (Stir) Extrusion process (FSE/FE):



- A solid-state materials processing technology uses a non-consumable die to produce extrudates.
- Friction between the die and material produces extensive plastic deformation and generates frictional heating to plasticize the materials.
- The softened material is extruded through the die under severe plastic deformation.

Friction Extrusion process:

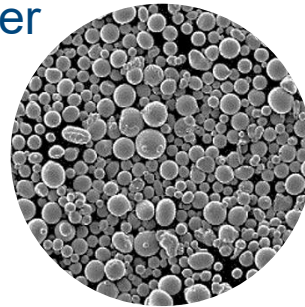
Process characteristics:

- **Solid state material processing:** low processing temperature, $0.8 T_{\text{melting}}$ (°K).
- **Low energy consumption:** no external heating, intrinsic frictional heating, low extrusion force.
- Able to process **different feedstock materials:**

Solid



Powder



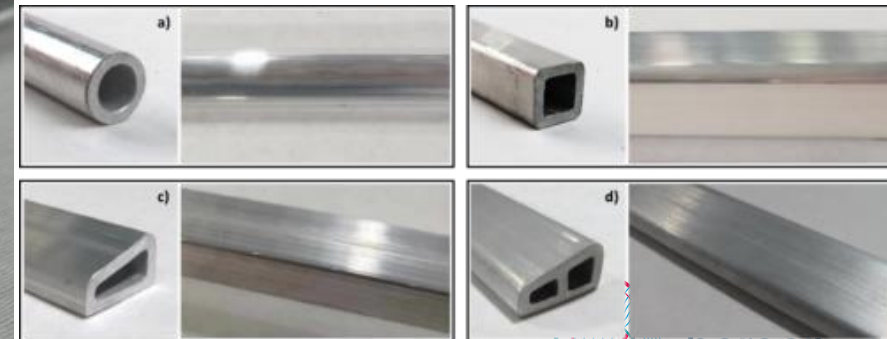
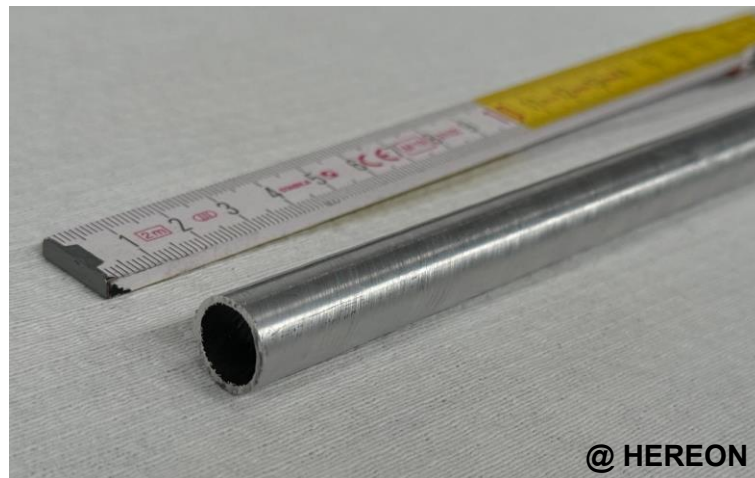
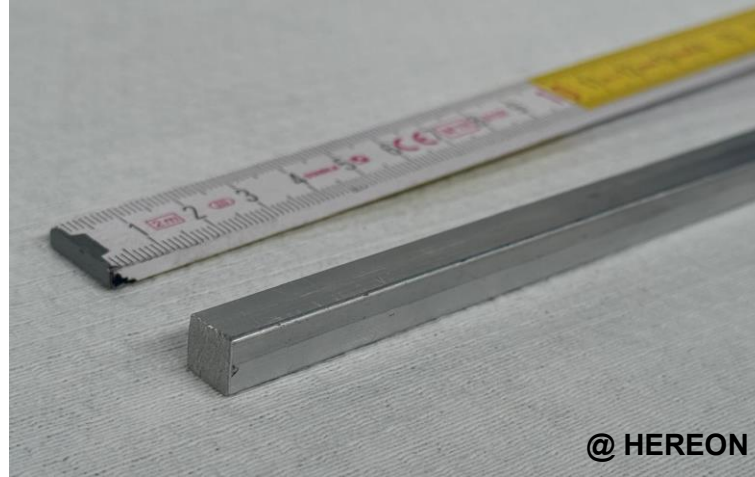
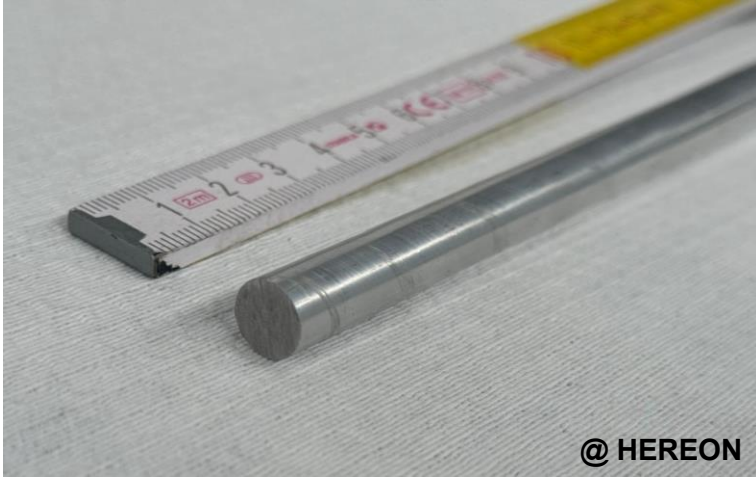
Machining chips



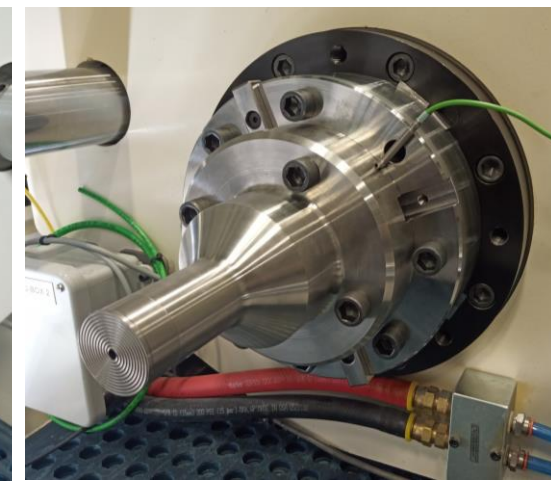
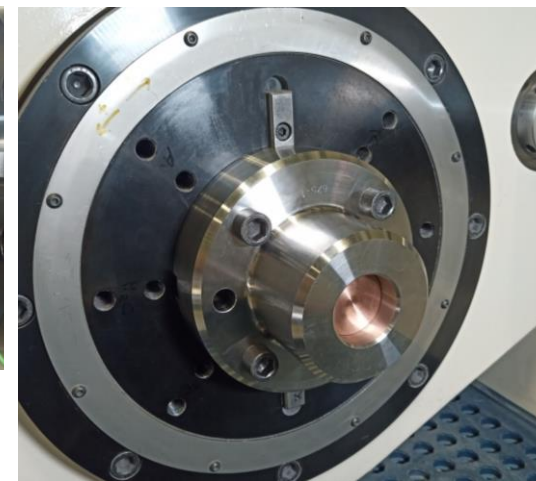
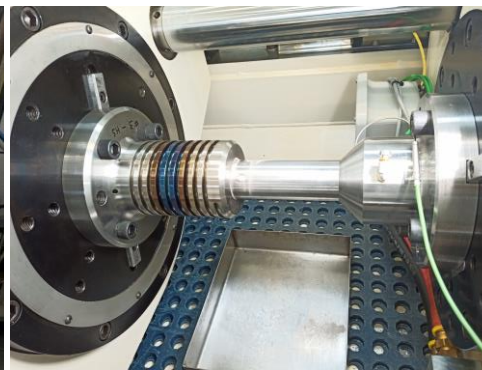
- Produce material with **advanced properties.**
- Feasibility demonstrated for processing **various metals:**
Al alloys (2000, 5000, 6000, 7000), Mg alloys, Cu alloy, entropy alloy, steel, Ti alloy....
- **Green technology:** high efficiency process (less material loss) and low carbon emission

Friction Extrusion process:

- Able to produce **various extrudates**: circular, square, hollow structure, profile.



Friction Extrusion Machines:



FE100 at Hereon

- Max force : 1000 kN
- Max Tailstock Velocity : 305 mm/min
- Rotation Speed Range : 0-1000 RPM
- Two-Speed Spindle
 - 1st Gear Torque : 3561 Nm @ 25 to 134 RPM
 - 2nd Gear Torque : 937 Nm @ 50 to 510 RPM



<https://bondtechnologies.net/>

Friction Extrusion of Solid, Powder and chips Materials

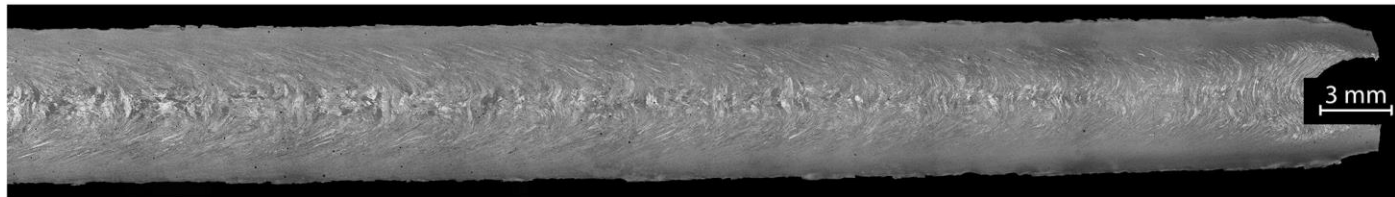
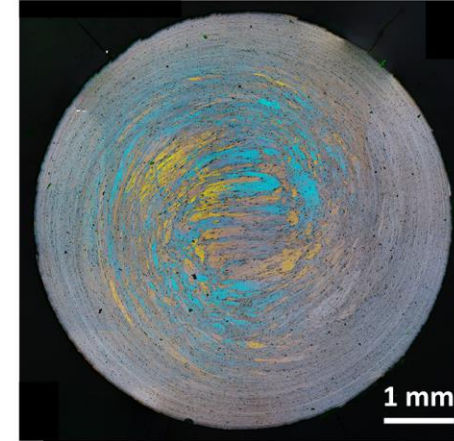


Feedstock Material

Chips – Powder - Solid

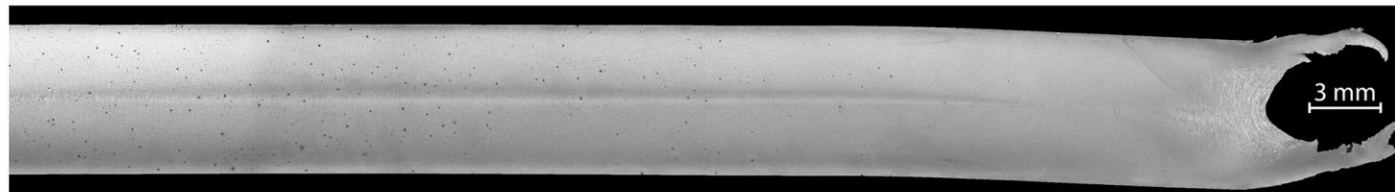
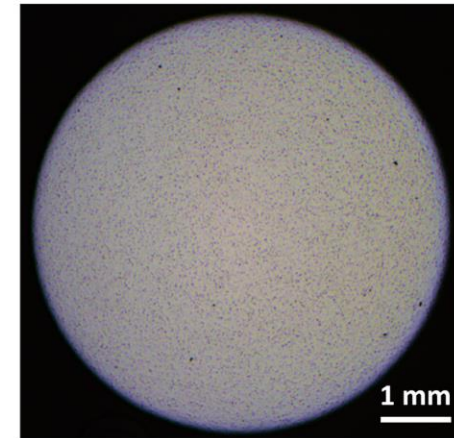
a.

Extrusion force < 19 kN



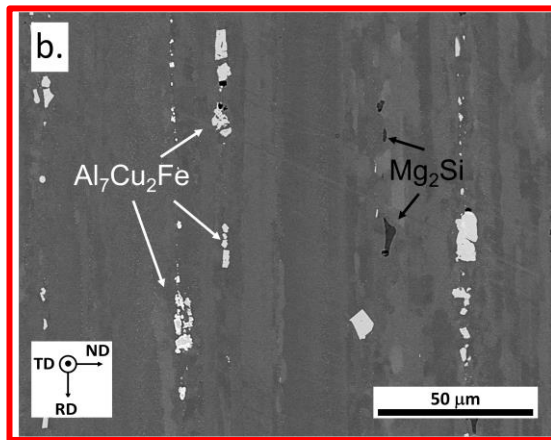
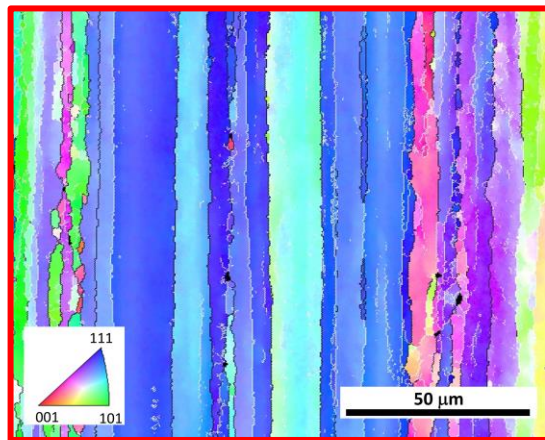
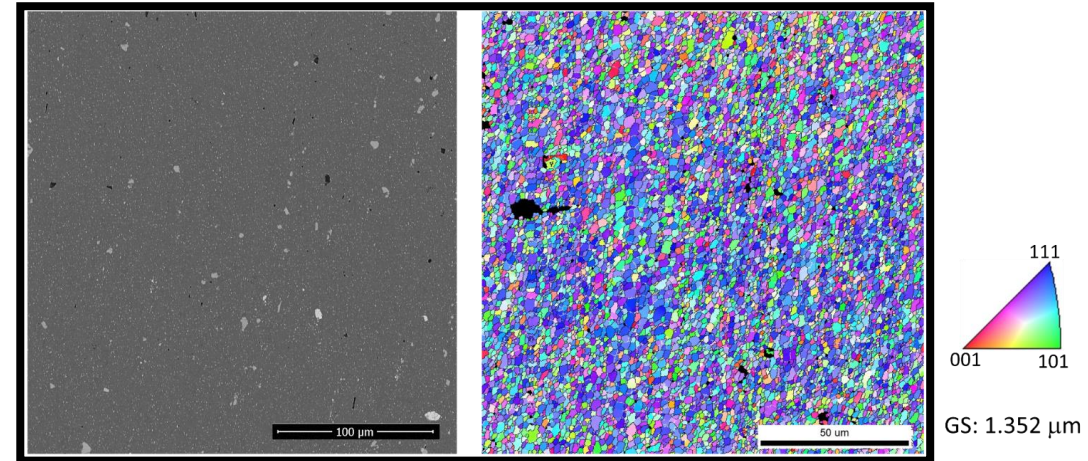
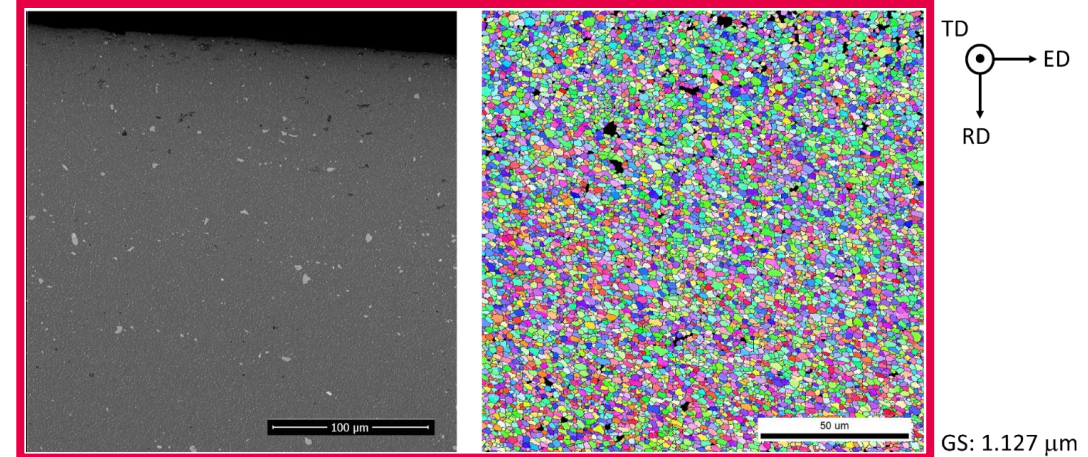
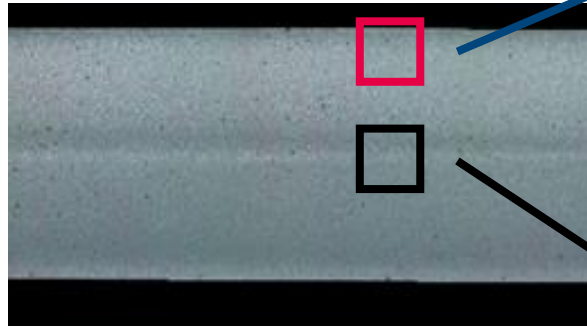
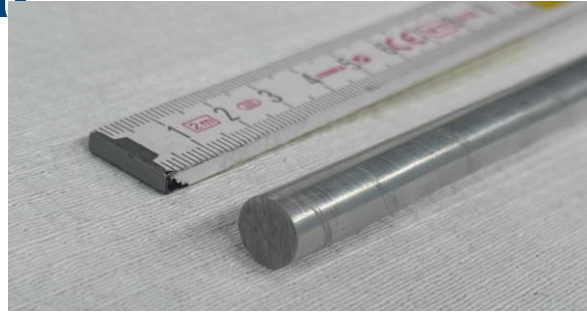
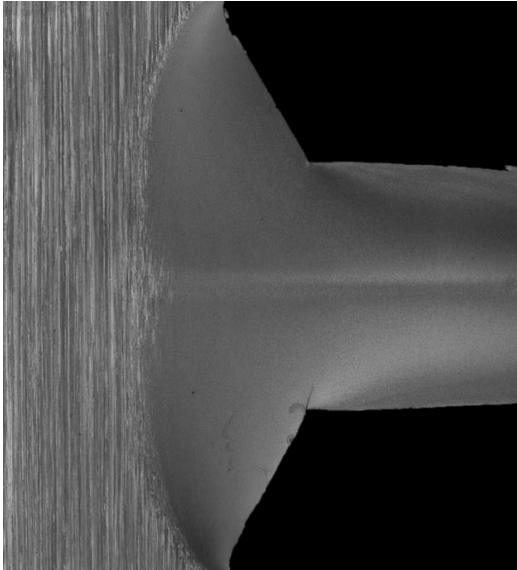
b.

Extrusion force > 19 kN



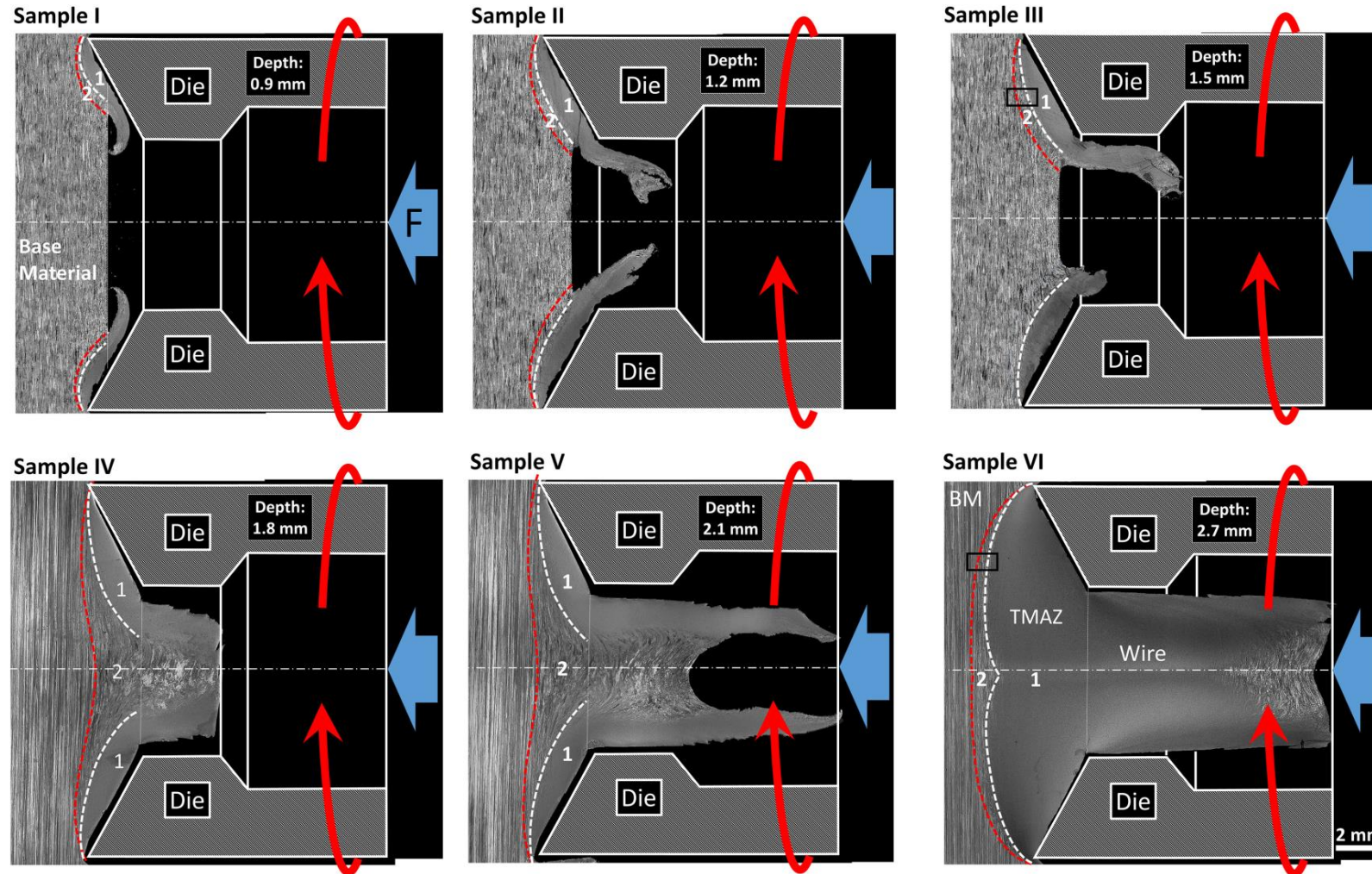
Feedstock Material

Chips – Powder - Bulk

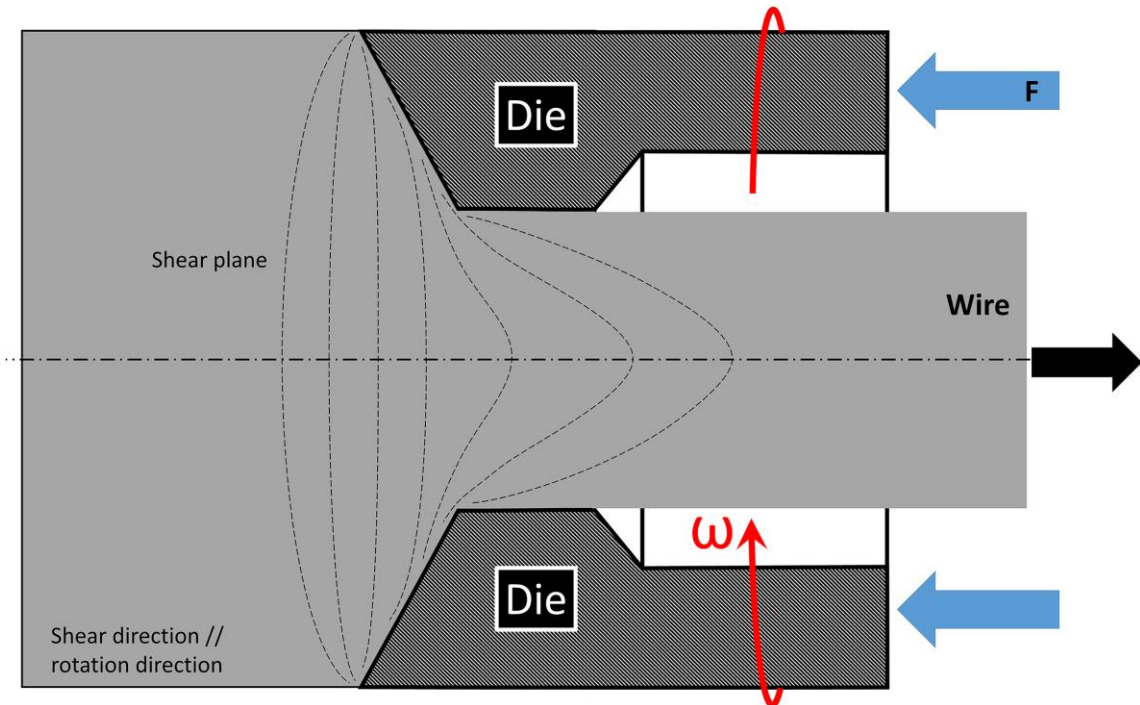
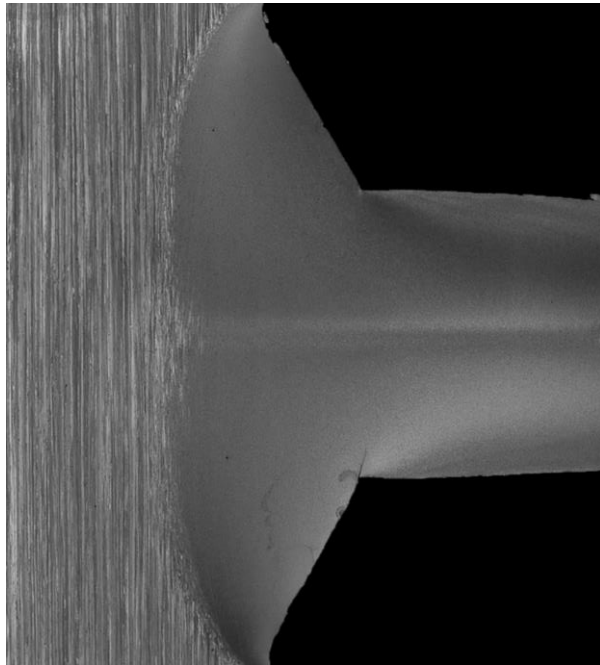
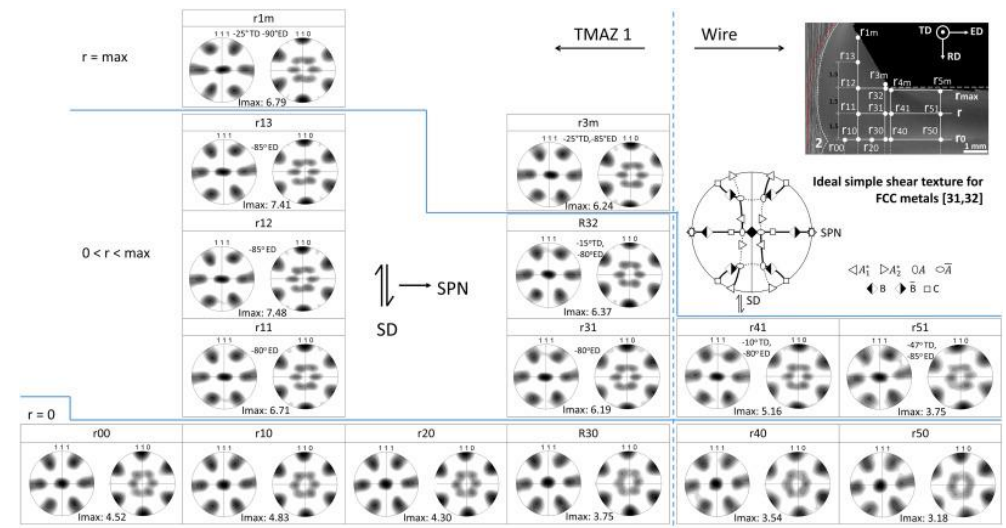
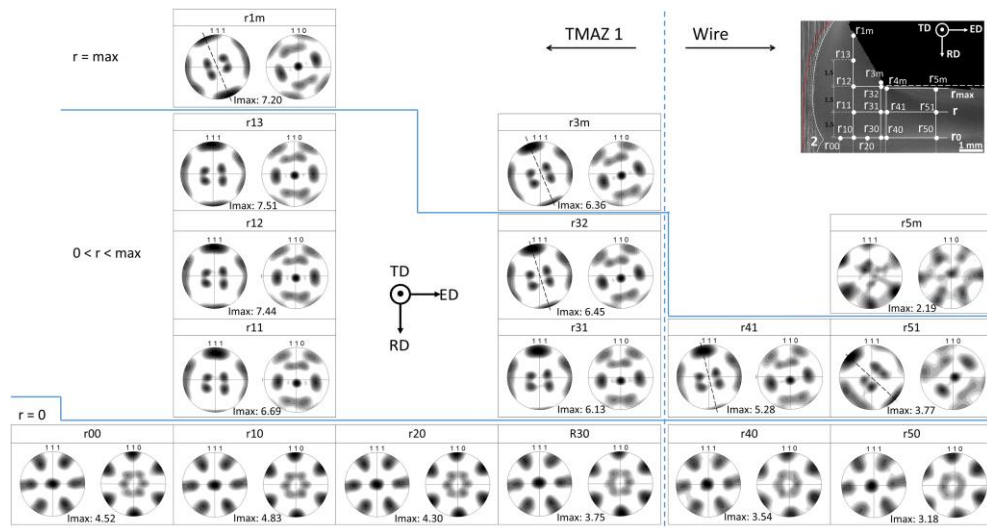


- Microstructure homogenization
- Grain refinement by dynamic recrystallization
- Improve material properties

Microstructure evolution during Friction Extrusion Bulk AA7075

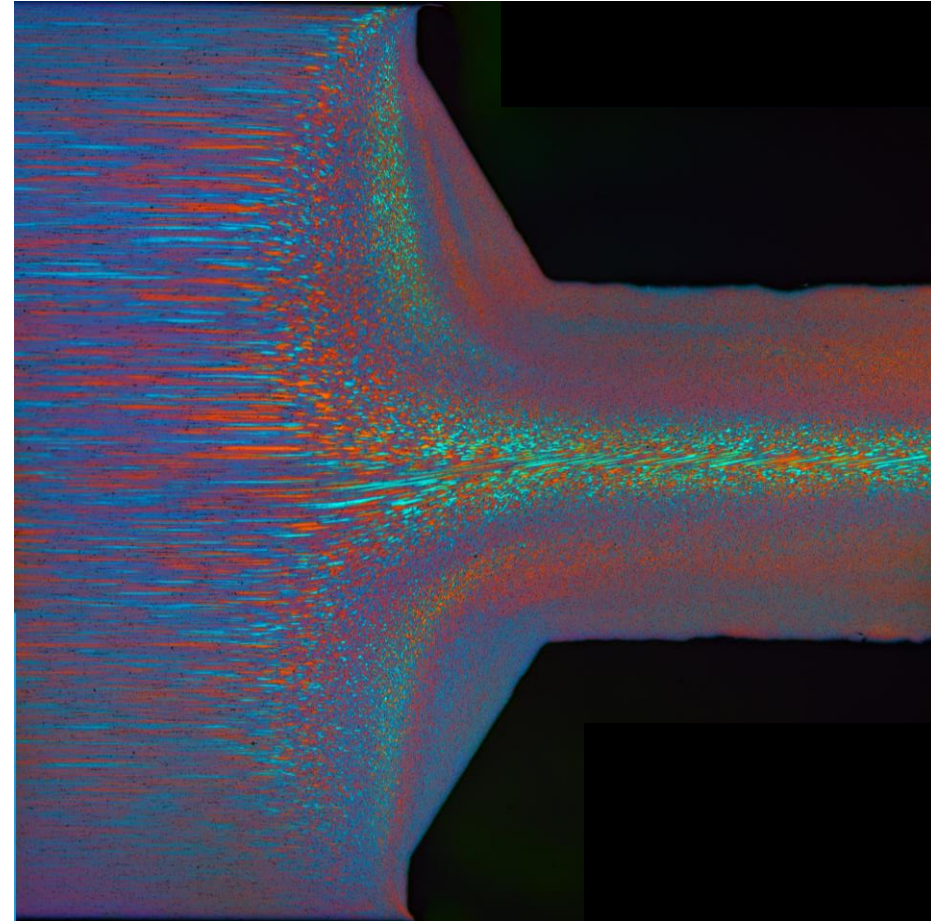
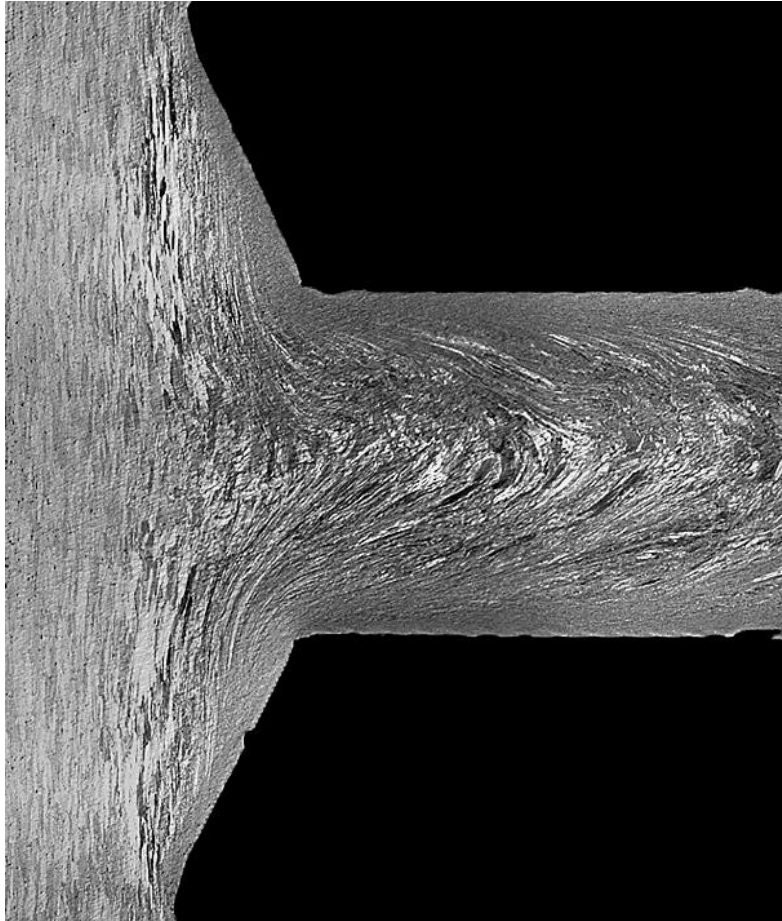


UFH. Suhuddin, L. Rath, RM Halak and B. Klusemann, "Microstructure evolution and texture development during production of homogeneous fine-grained aluminum wire by friction extrusion". *Materials Characterization*, 205 (2023) 113252.

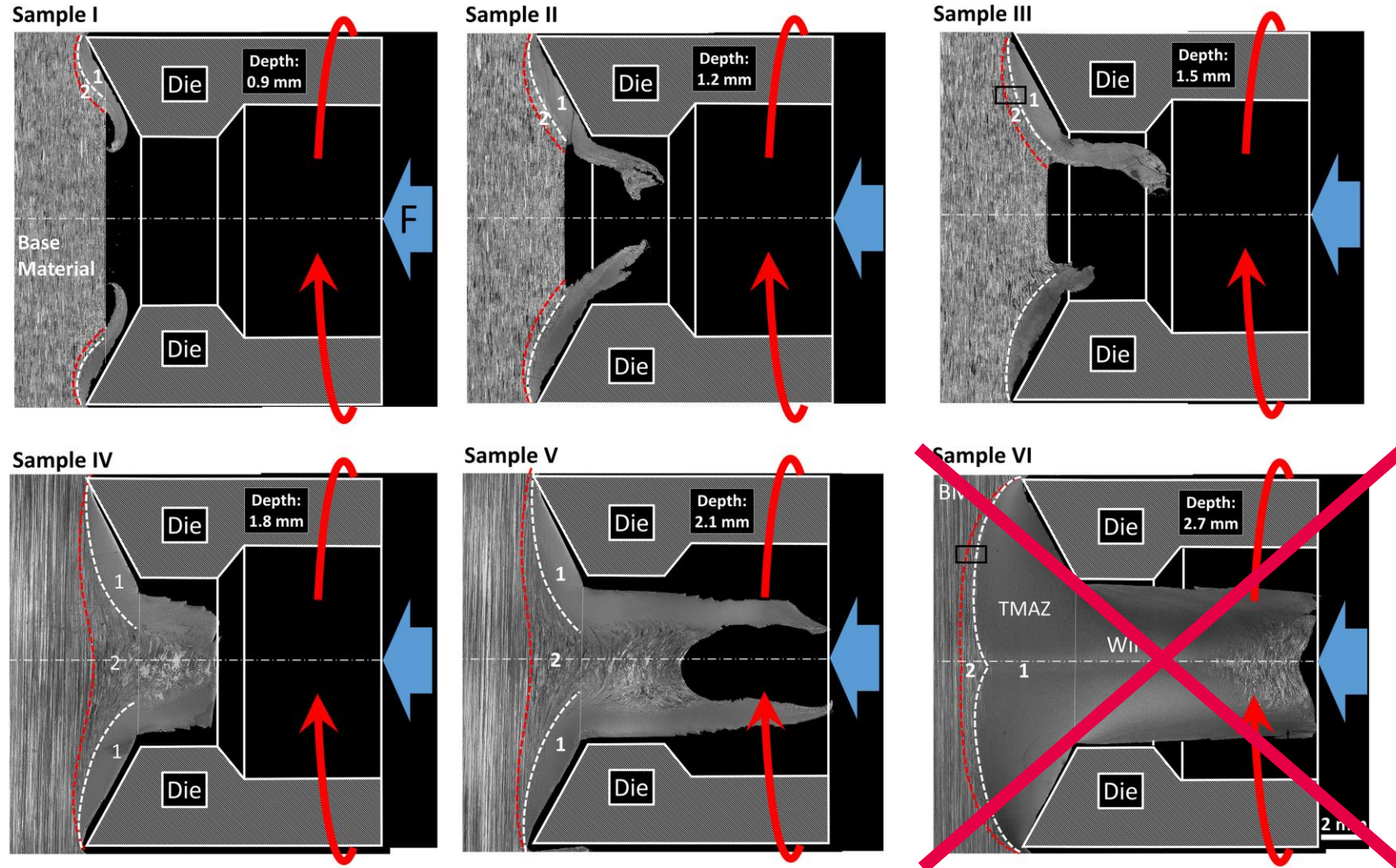


UFH. Suhuddin, L. Rath, RM Halak, B. Klusemann, "Microstructure evolution and texture development during production of homogeneous fine-grained aluminum wire by friction extrusion". *Materials Characterization*, 205 (2023) 113252.

Microstructure evolution during Friction Extrusion Bulk AA7075

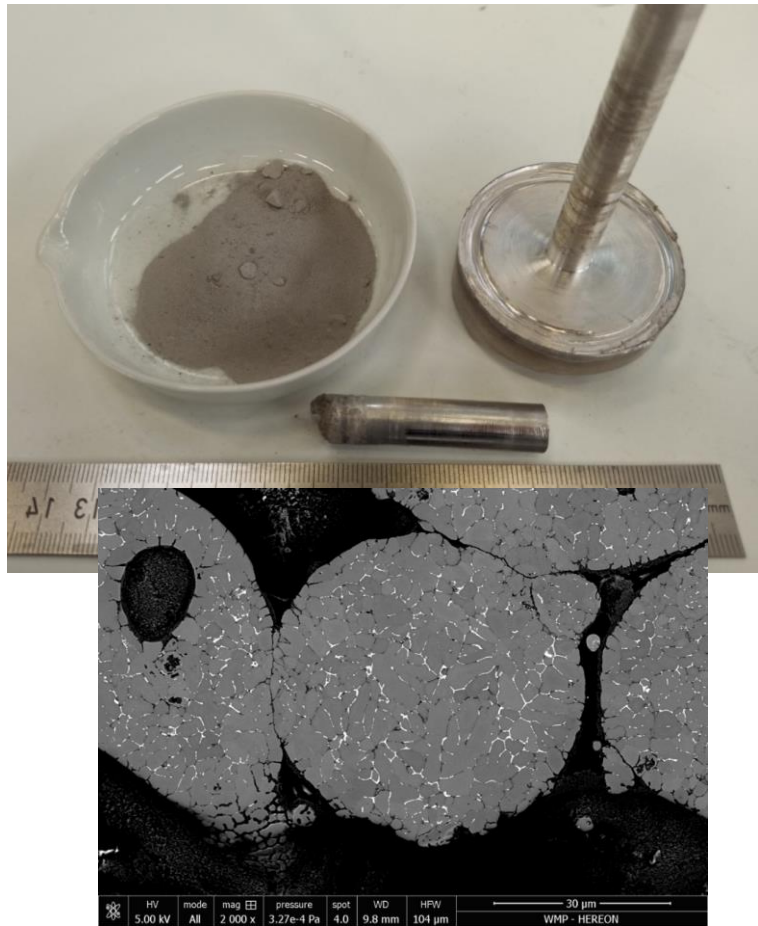


Microstructure evolution during Friction Extrusion Bulk AA7075

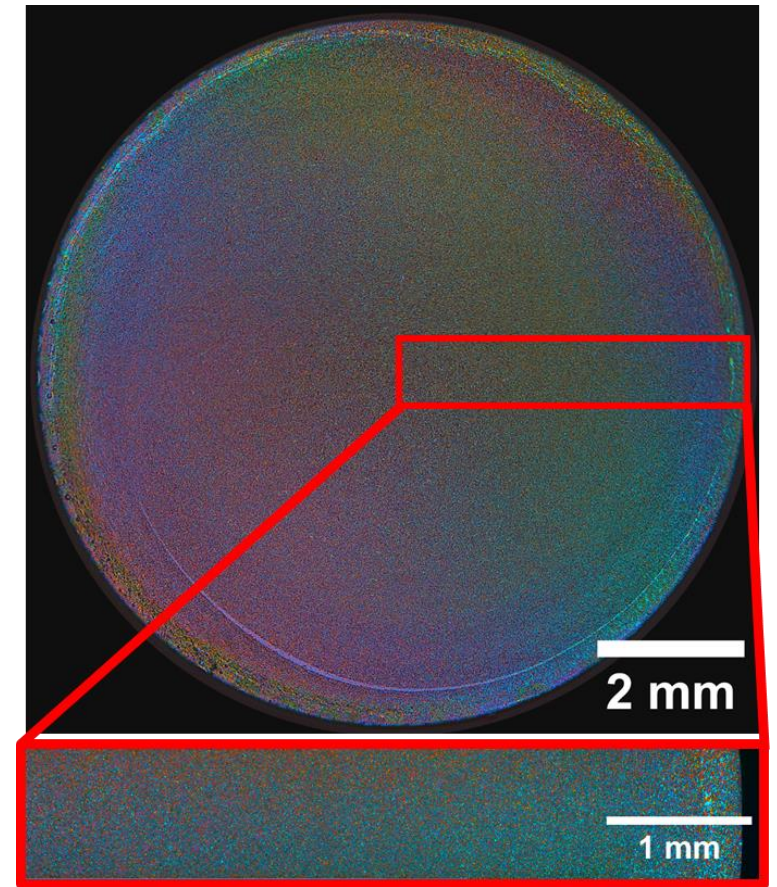
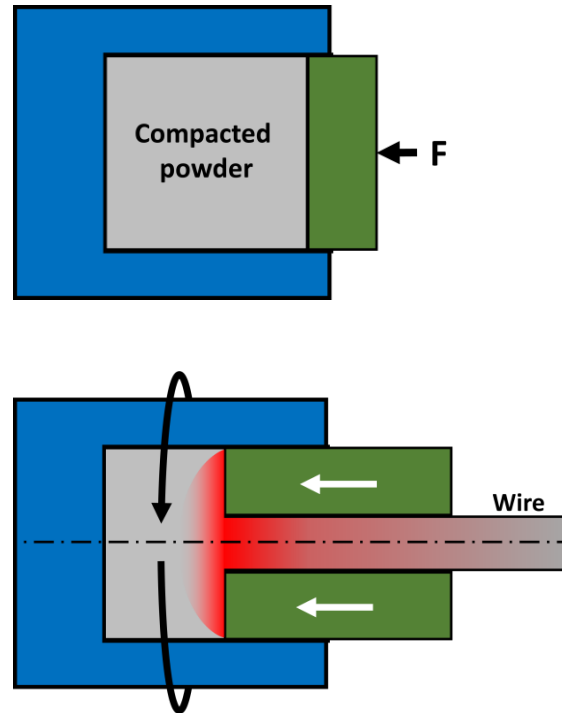


Feedstock Material

Powder – Chips – Solid



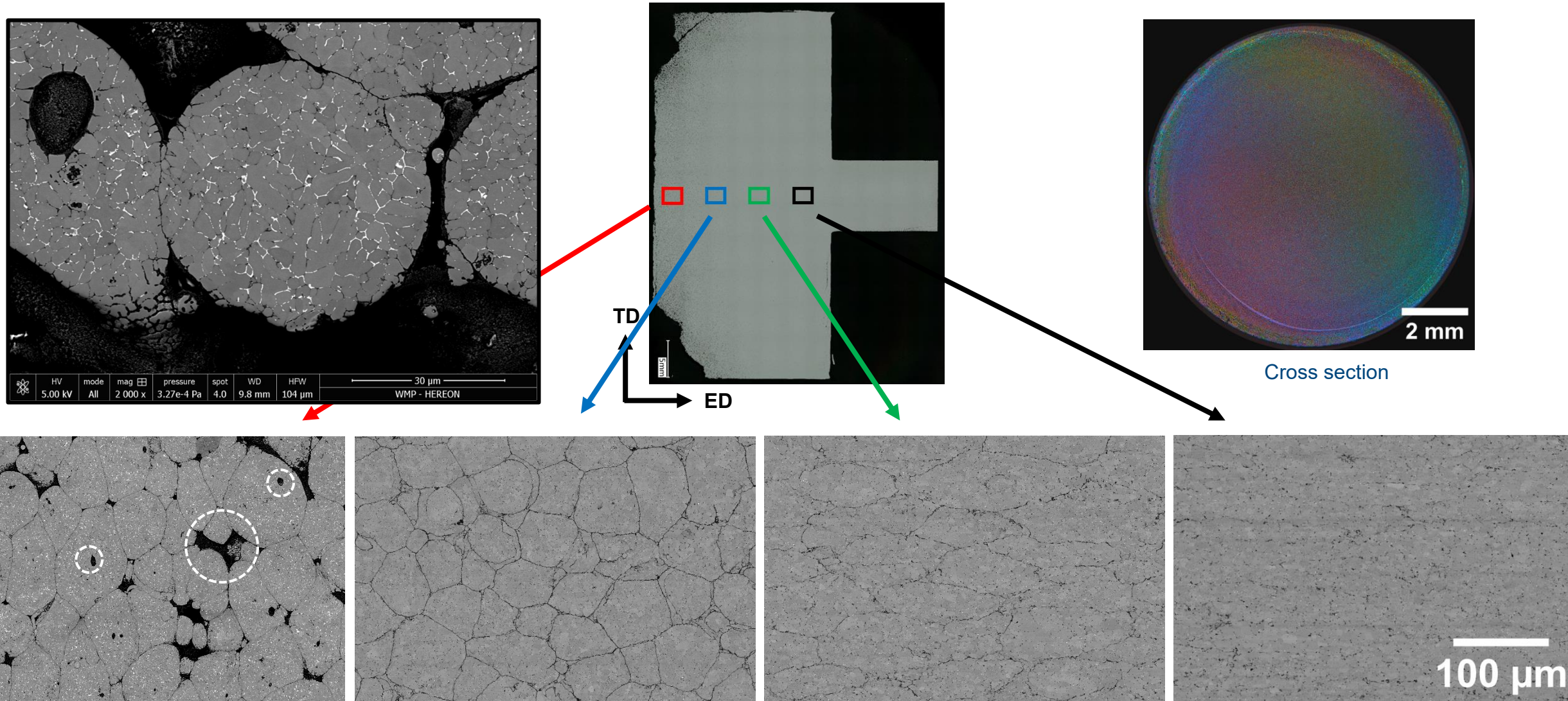
AA 7075 powder



Chan CYC, Rath L, Suhuddin UFH, Klusemann B, Friction extrusion processing of aluminum powders: Microstructure homogeneity and mechanical properties, Materials Research Proceedings. 28 (2023) 515-522. DOI: <https://doi.org/10.21741/9781644902479-56>

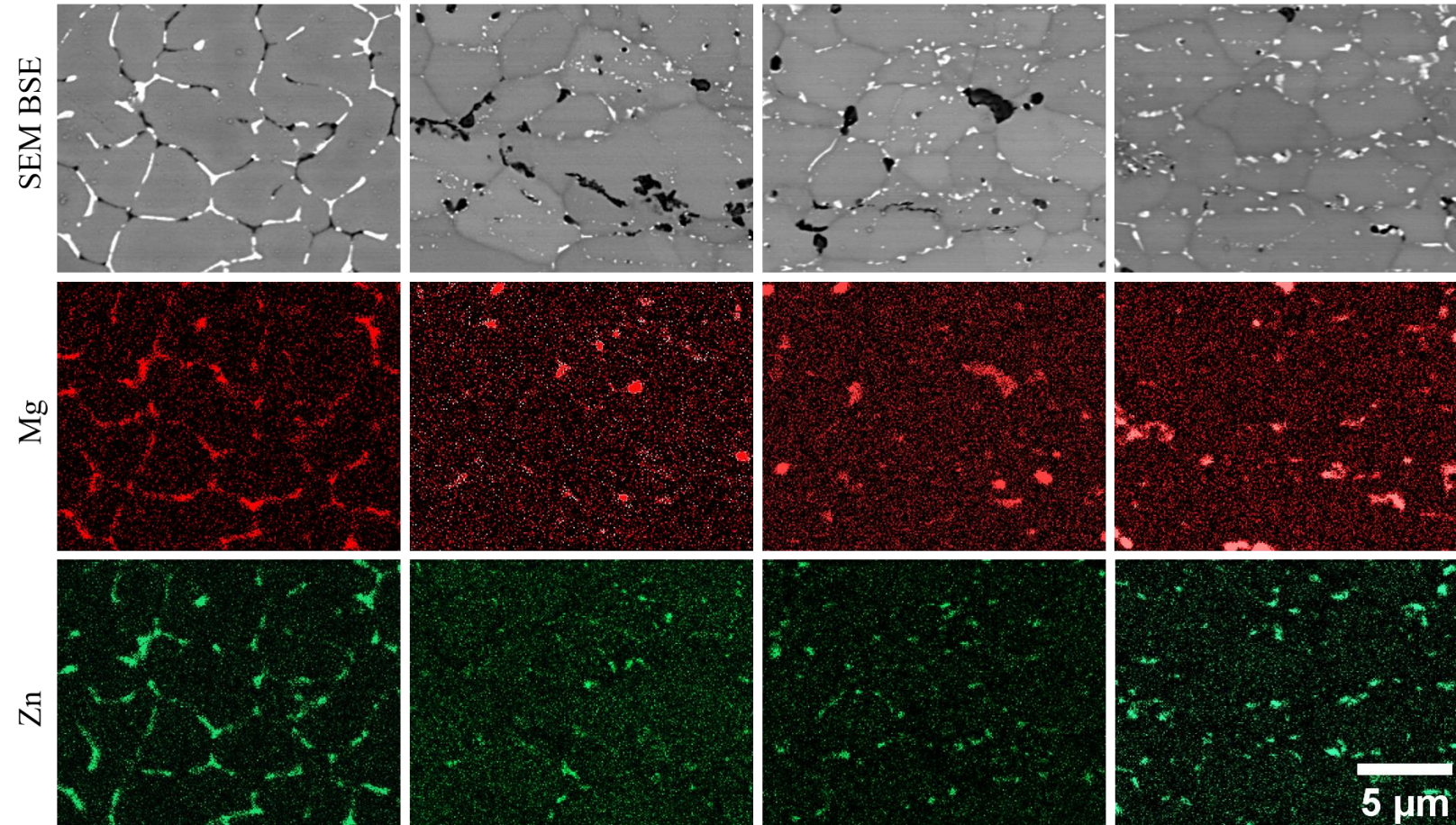
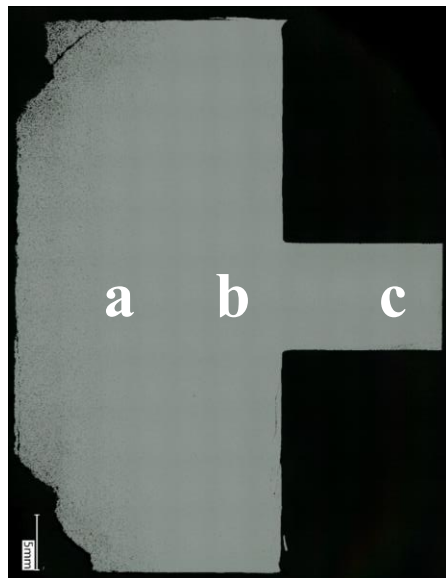
Feedstock Material

Powder – Chips – Bulk



Feedstock Material

Powder – Chips – Bulk



Base material

a

b

c

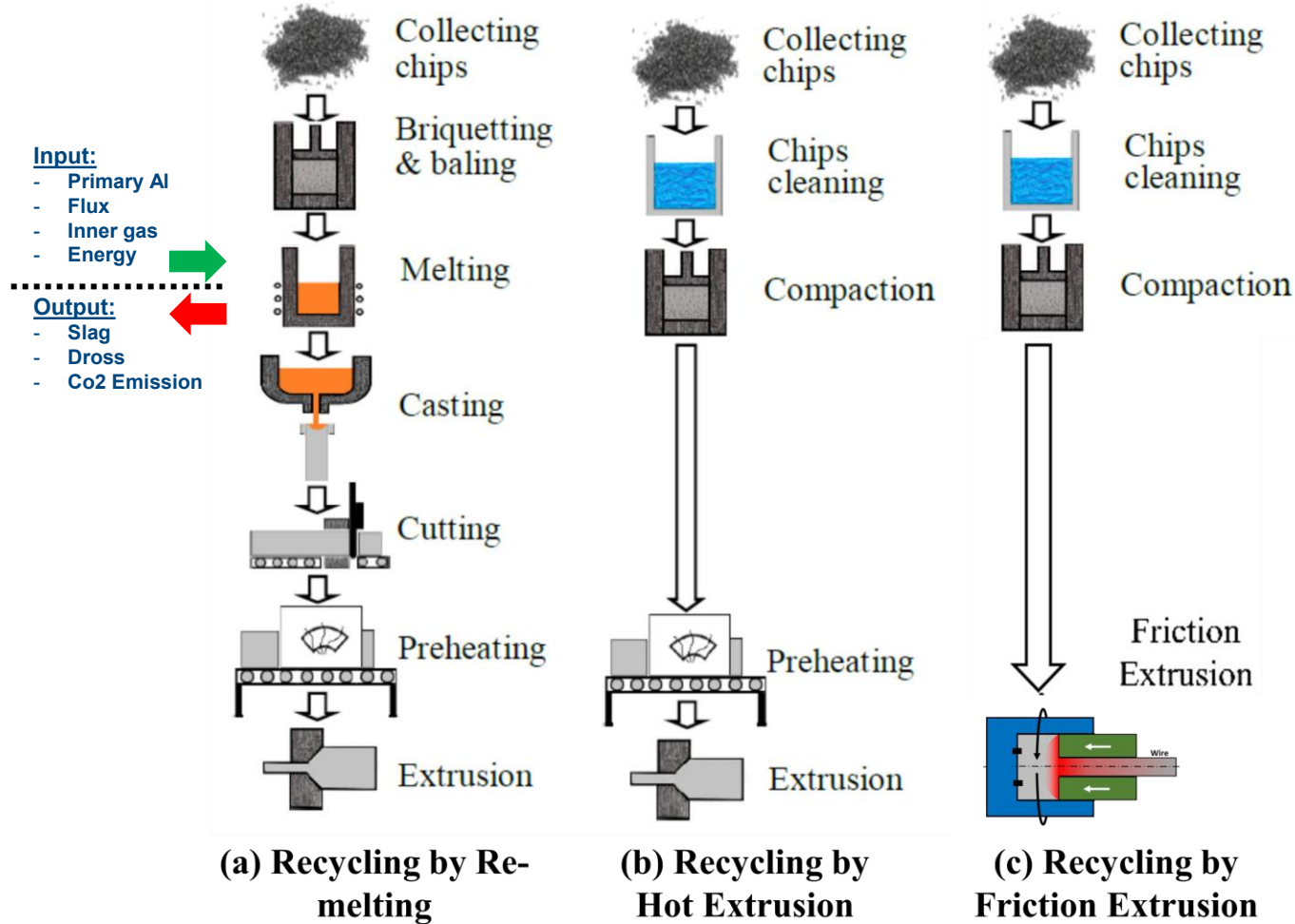


Friction Extrusion for Materials Recycling



Friction Extrusion for Recycling Materials

Solid-state recycling



Re-melting vs Solid state recycling

- Up to 90% energy saving : process chain from re-melting – extrusion billet
- 20 – 50% material lost reduction
- No defects from melting process

V. Güley, N. Ben Khalifa, A. E. Tekkaya, Int J Mater Form 3 (2010)
DOI 10.1007/s12289-010-0904-z

A Wagiman, MS Mustapa, R Asmawi, S Shamsudin, MA Lajis, Y Mutoh, A review on direct hot extrusion technique in recycling of aluminium chips, The International Journal of Advanced Manufacturing Technology 106 (2020) 641–653.
<https://doi.org/10.1007/s00170-019-04629-7>

Recycling Material

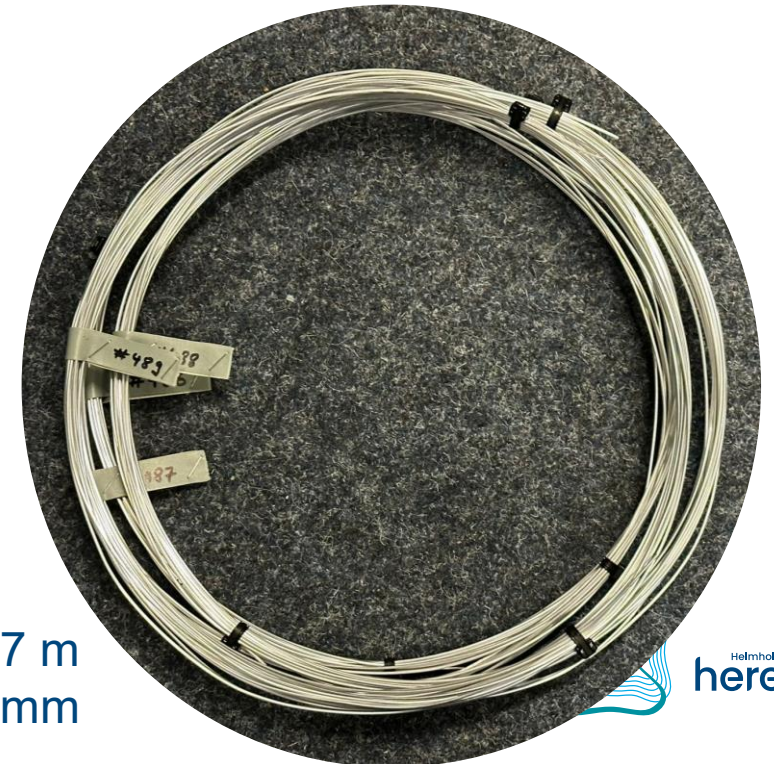
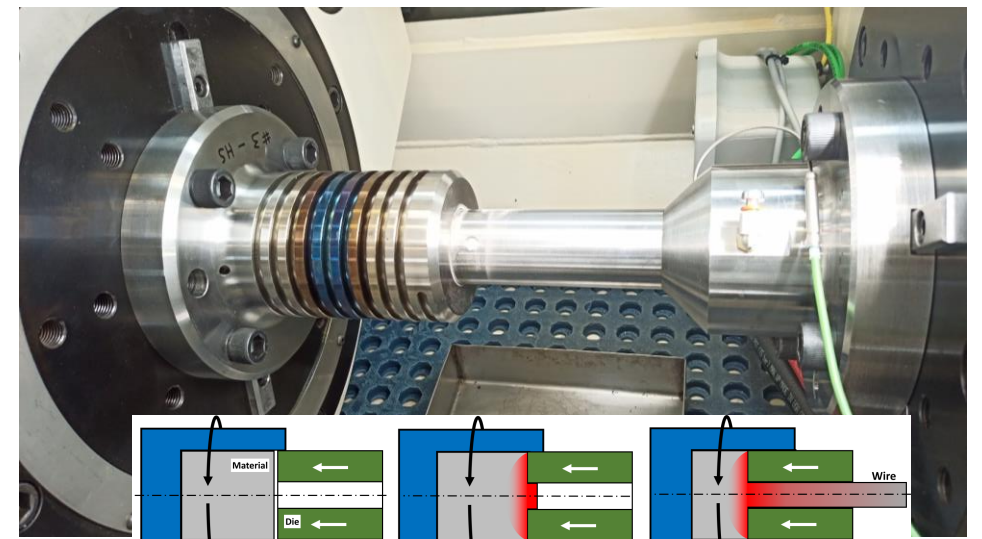
AA6082 Machining Chips



Lathe machine



compaction



GP Ignacio, LR Rath, Uceu F.H. Suhuddin, B. Klusemann, Friction extrusion from AlMgSi machining waste at high extrusion ratio, Materials Research Proceedings 54 (2025) 735-744. <https://doi.org/10.21741/9781644903599-79>

- Length: 18.7 m
- Wire diameter: 1.5 mm

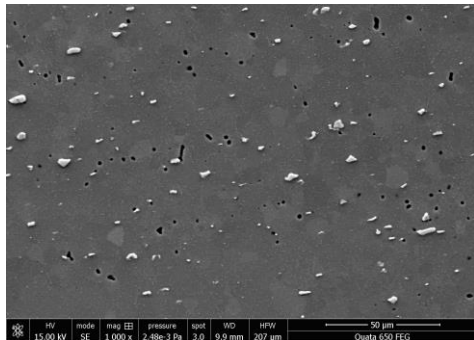
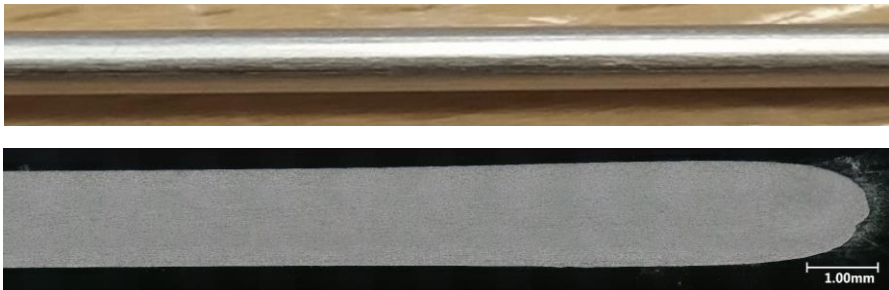
Extrudate - Wire

Chips

From material characteristic, the wire is divided to 3 segments:

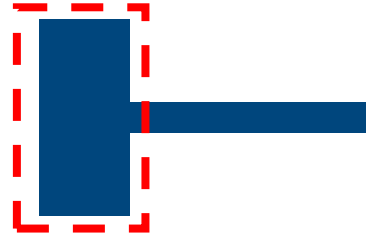
- 1st segment: 1 – 9 m
- 2nd segment: 9 – 15 m
- 3rd segment: 15 – 18 m

Chips, 1.5 mm



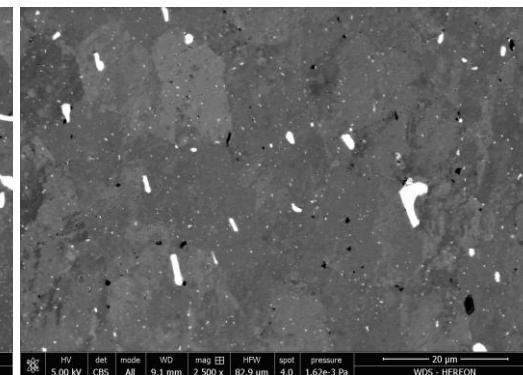
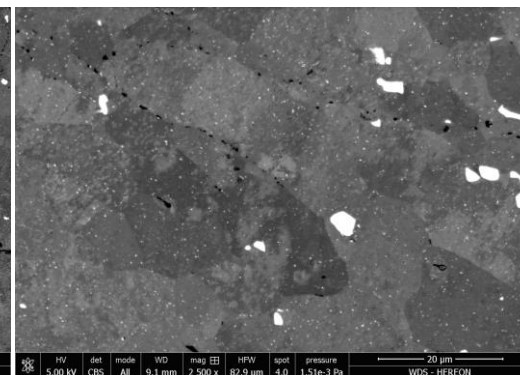
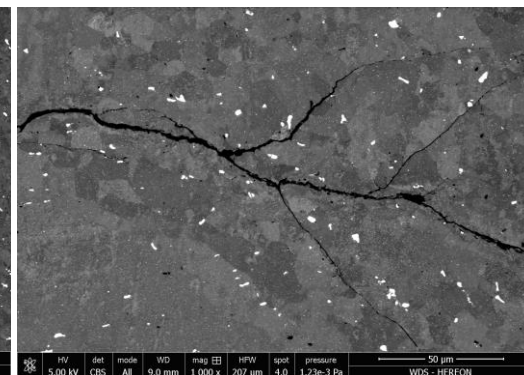
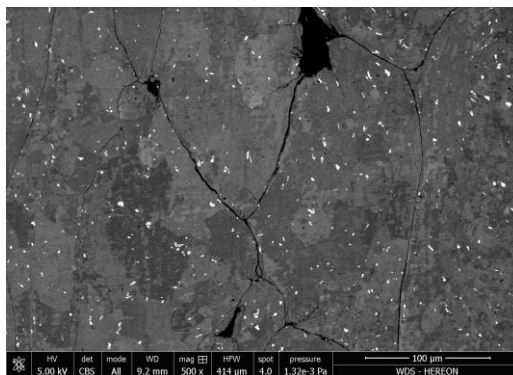
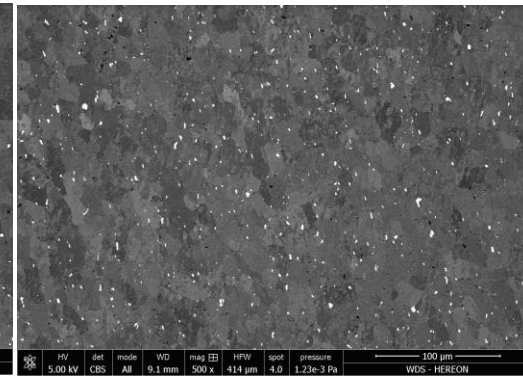
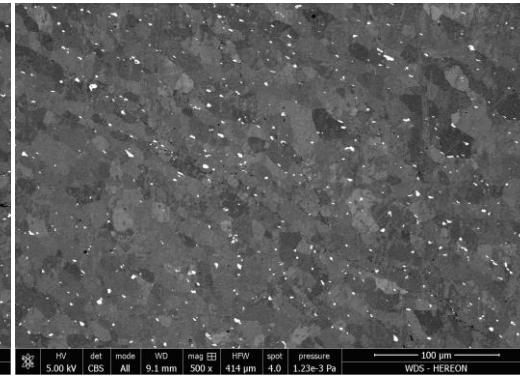
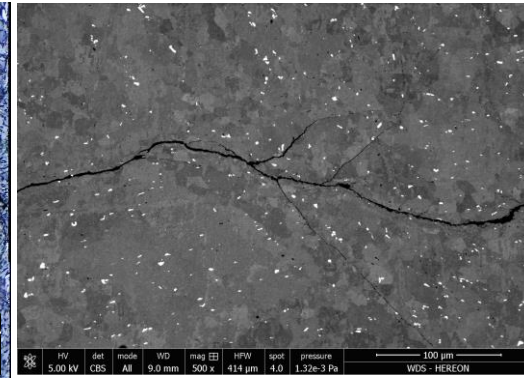
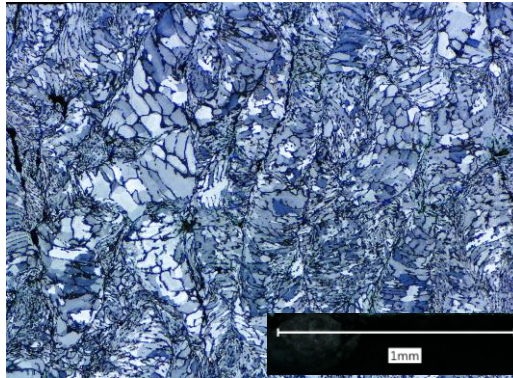
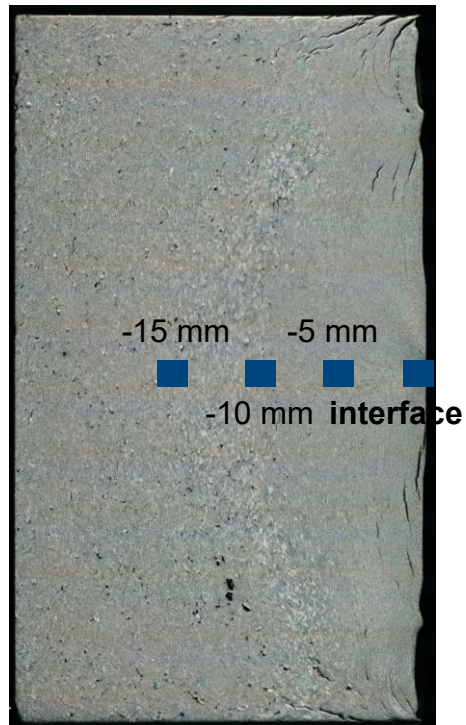
Material Characterization

Residual material



Evolution during FE:

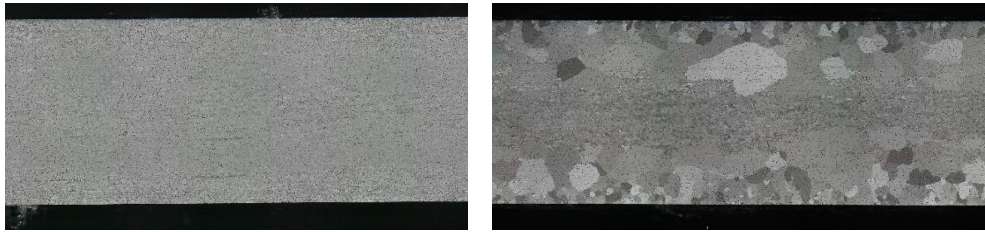
- Porosity and powder boundary (size, orientation)
- Microstructure (homogeneity)
- Bright particles, AlFeSi (distribution)



Extrudate - Wire

Microstructure

Tip (1 – 9 m)



Middle (9 – 15 m)

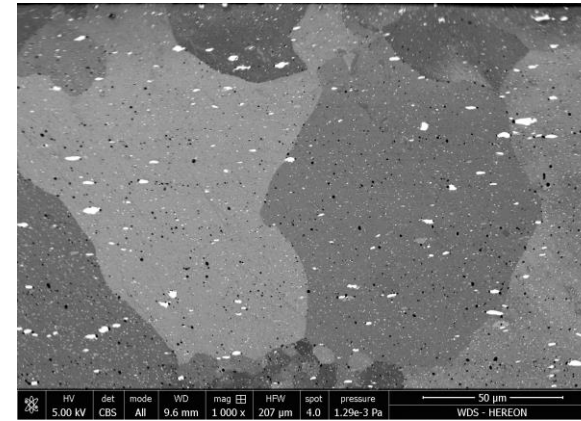


End (15 – 18 m)

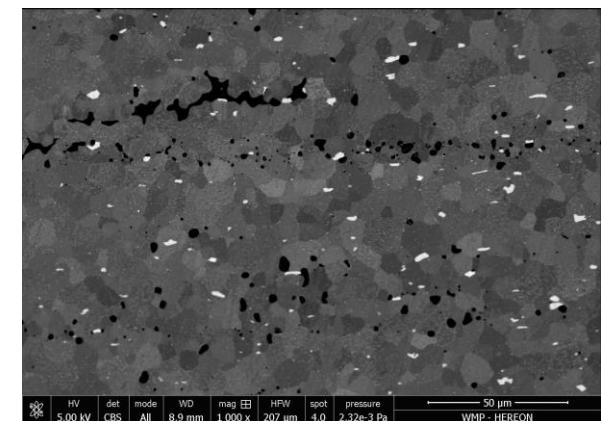
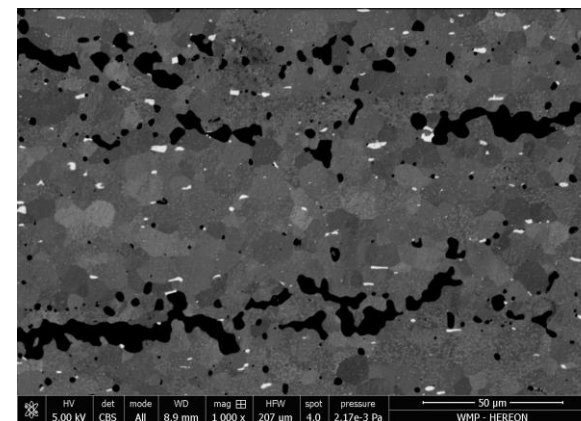
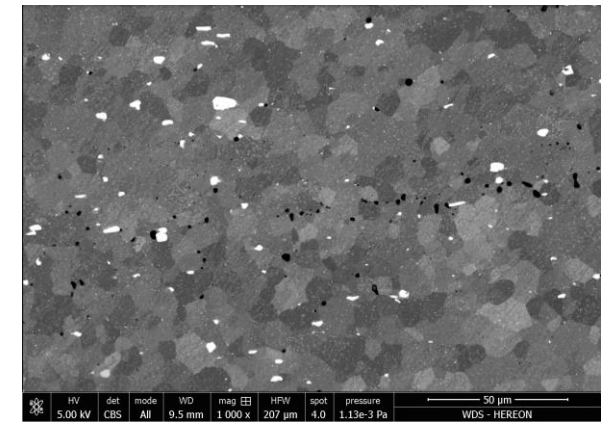
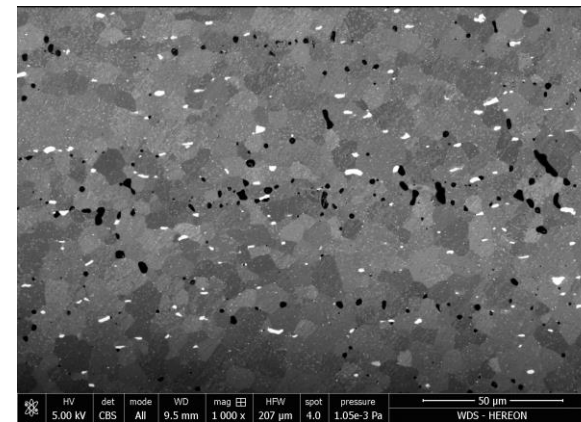
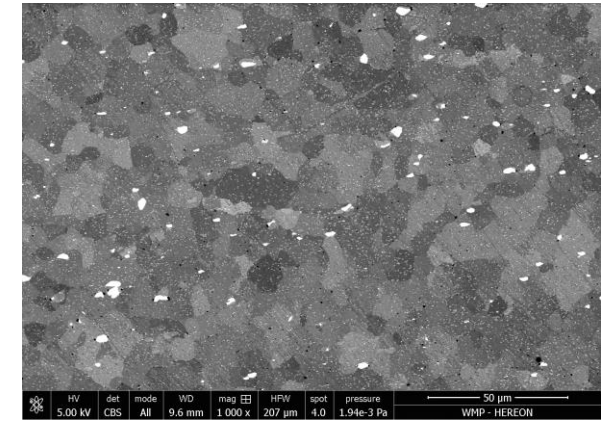


- No cooling apply during the process, leads to heat accumulation
- Thermal management by proper cooling system could avoid the inhomogeneity

Edge

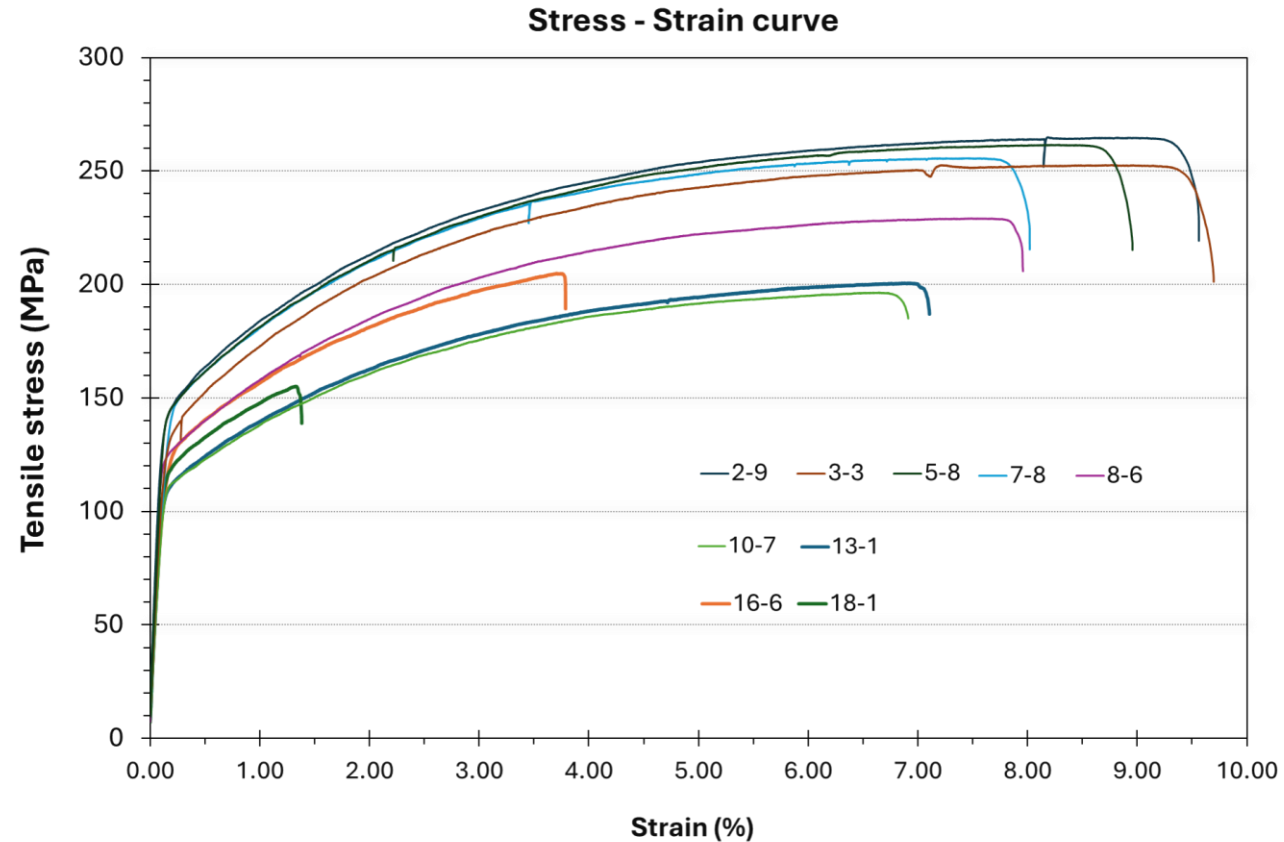
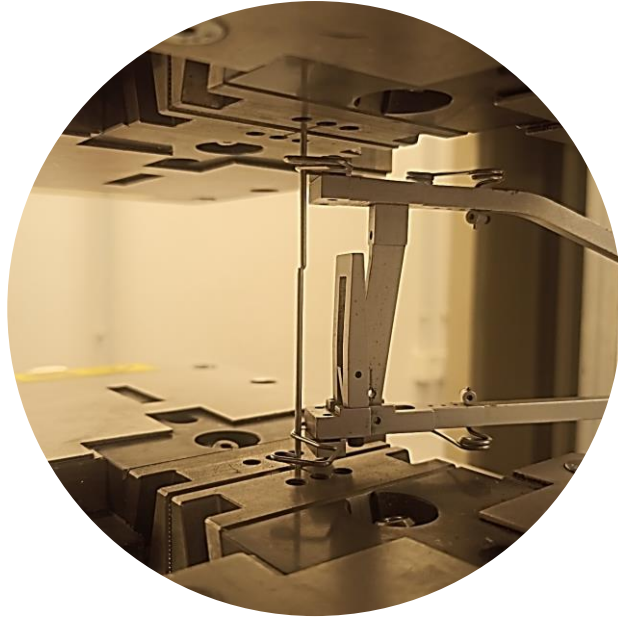


Center



Extrudate - Wire

Mechanical property



AA6082	Temper			Friction extrusion		
	O	T4	T6	1 st	2 nd	3 rd
Properties						
UTS (MPa)	130	205	290 – 310	220 - 265	180 – 200	150 – 210
YS (MPa)	60	110	250 – 260	130 - 150	100 - 120	110 - 130
Elongation at break (%)	27	14	10	7.5 – 9.5	6.5 – 7.5	1.5 – 4.0

GP Ignacio, LR Rath, Uceu F.H. Suhuddin, B. Klusemann, Friction extrusion from AlMgSi machining waste at high extrusion ratio, Materials Research Proceedings 54 (2025) 735-744. <https://doi.org/10.21741/9781644903599-79>

Friction Extrusion for Materials Upcycling

Friction Extrusion: An Emerging Solid-State Technique

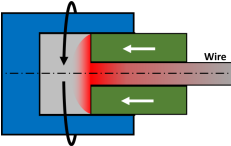
Friction Extrusion for Materials Upcycling

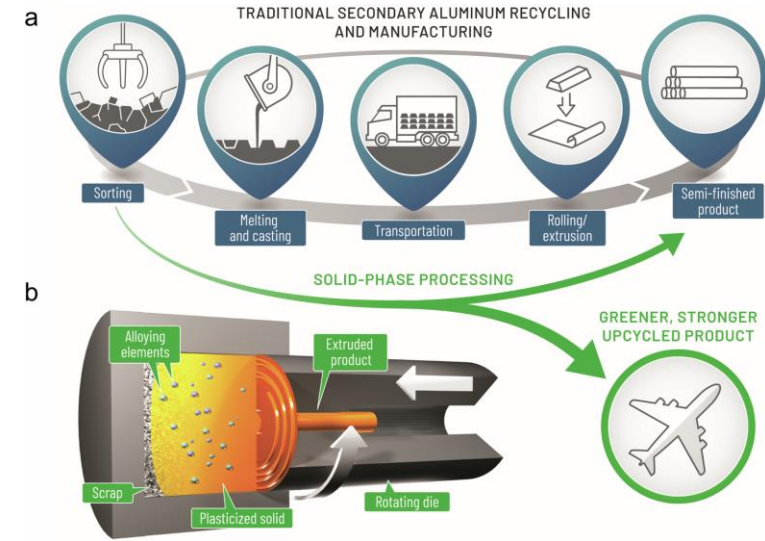
Recycling vs Upcycling

Recycle:

6063 Al alloy →  → 6063 Extrudate scrap

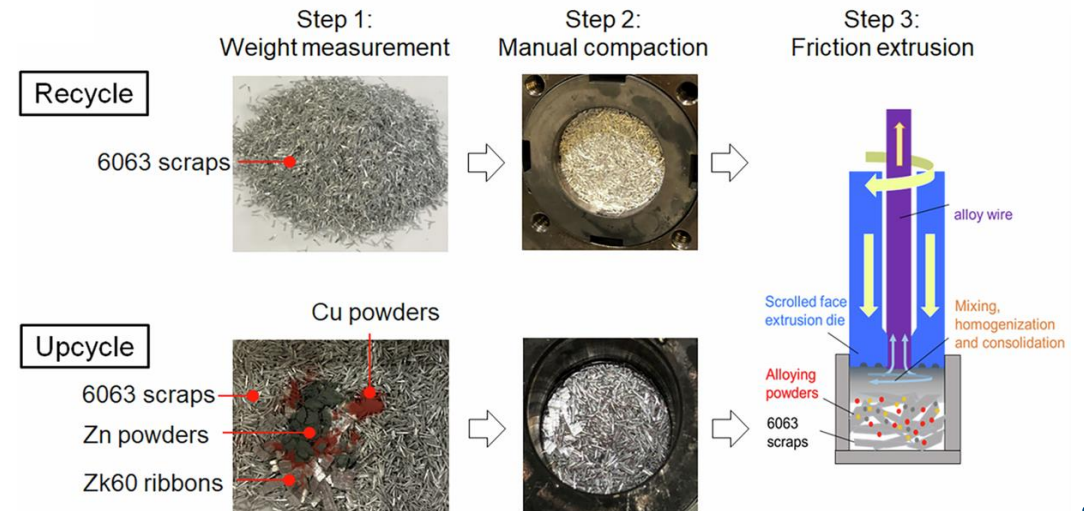
Upcycle:

6063 Al + Zn + Mg + Cu →  → 7075 Extrudate

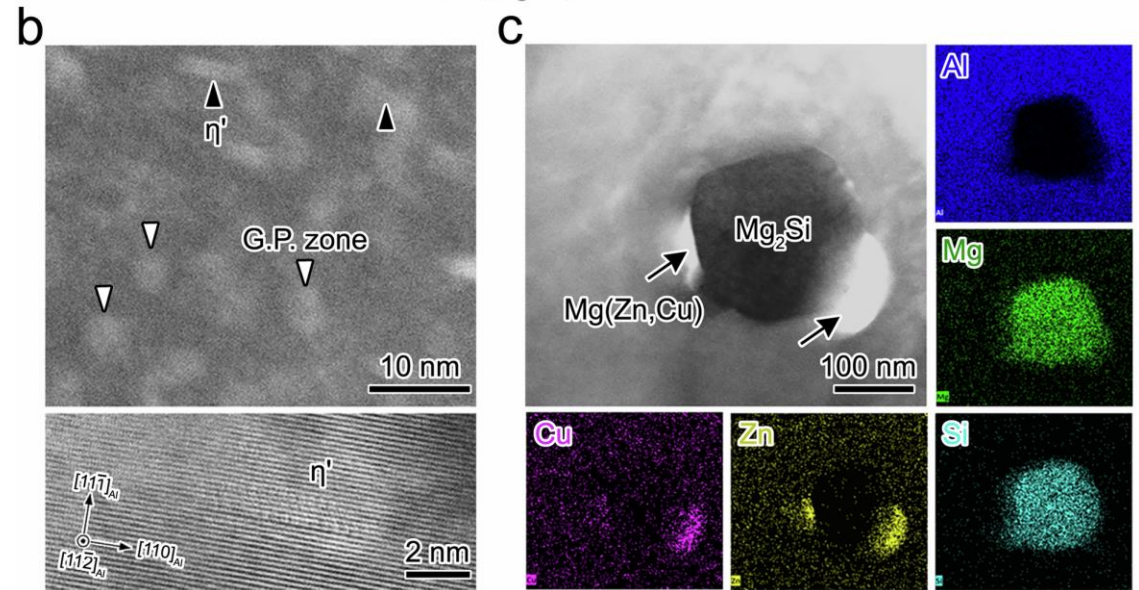
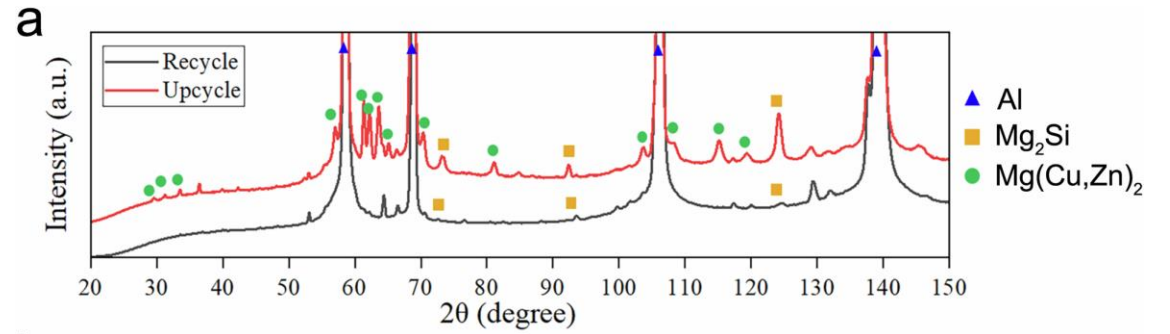
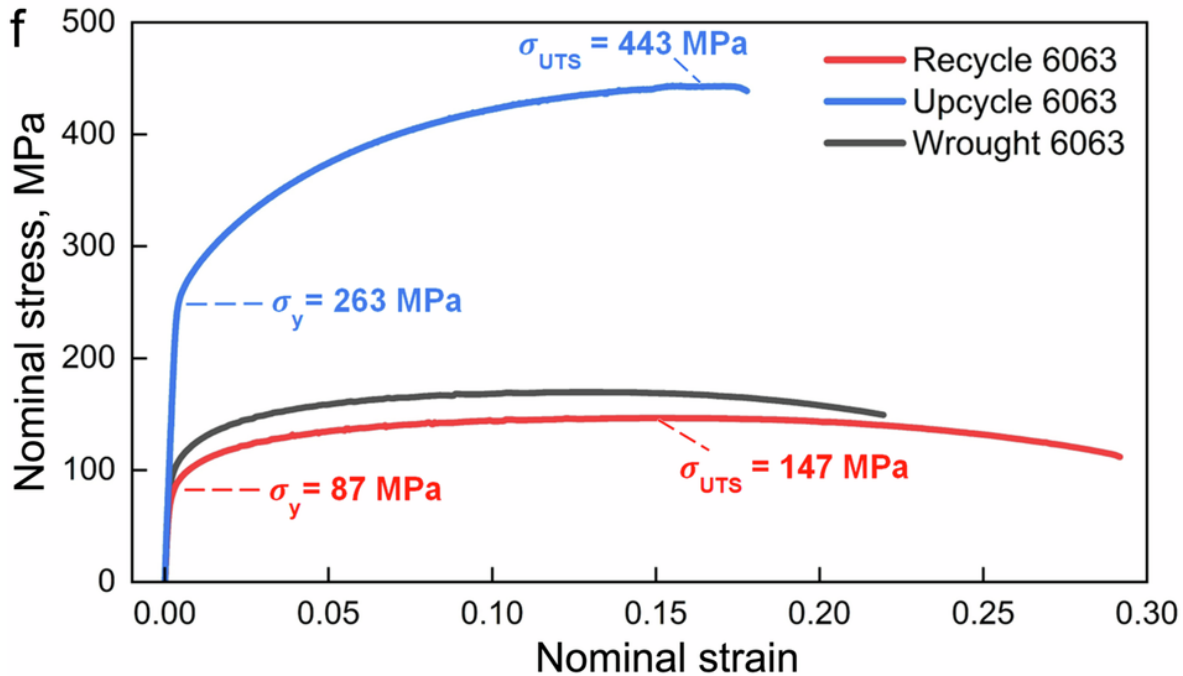
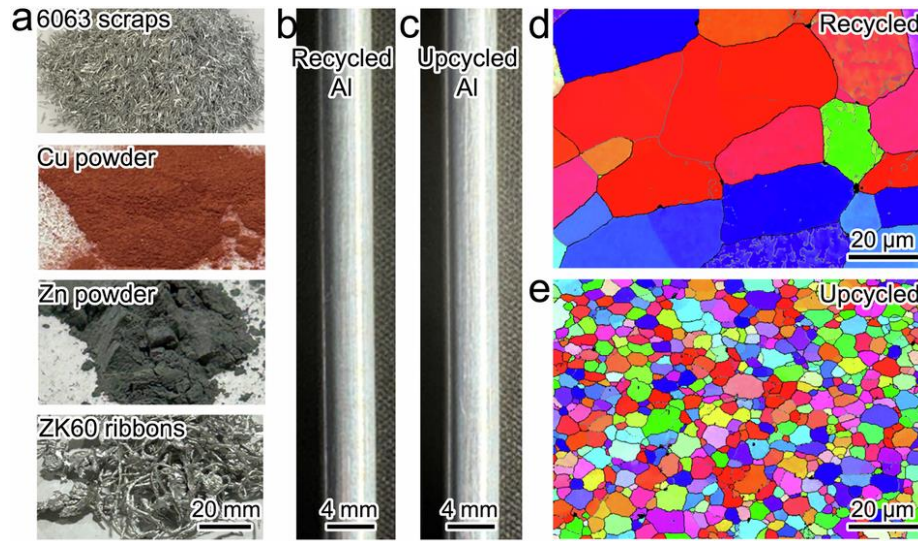


Material	Chemical composition (wt. %)						
	Al	Mg	Si	Zn	Cu	Fe	Zr
6063 scraps	Bal.	0.45	0.4	0.02	0.02	0.2	-
Cu powders	-	-	-	-	100	-	-
Zn powders	-	-	-	100	-	-	-
ZK60 ribbons	-	Bal.	-	5-5.5	-	-	0.57
Mixed precursor	Bal.	2.5	0.4	5.6	1.6	0.2	0.01
Standard 7075 Al	Bal.	2.1-2.5	0-0.5	5.6-6.1	1.2-1.6	0-0.5	0

Wang, T., Li, X., Li, Z. *et al.* Upcycled high-strength aluminum alloys from scrap through solid-phase alloying. *Nat Commun* 15, 10664 (2024). <https://doi.org/10.1038/s41467-024-53062-2>

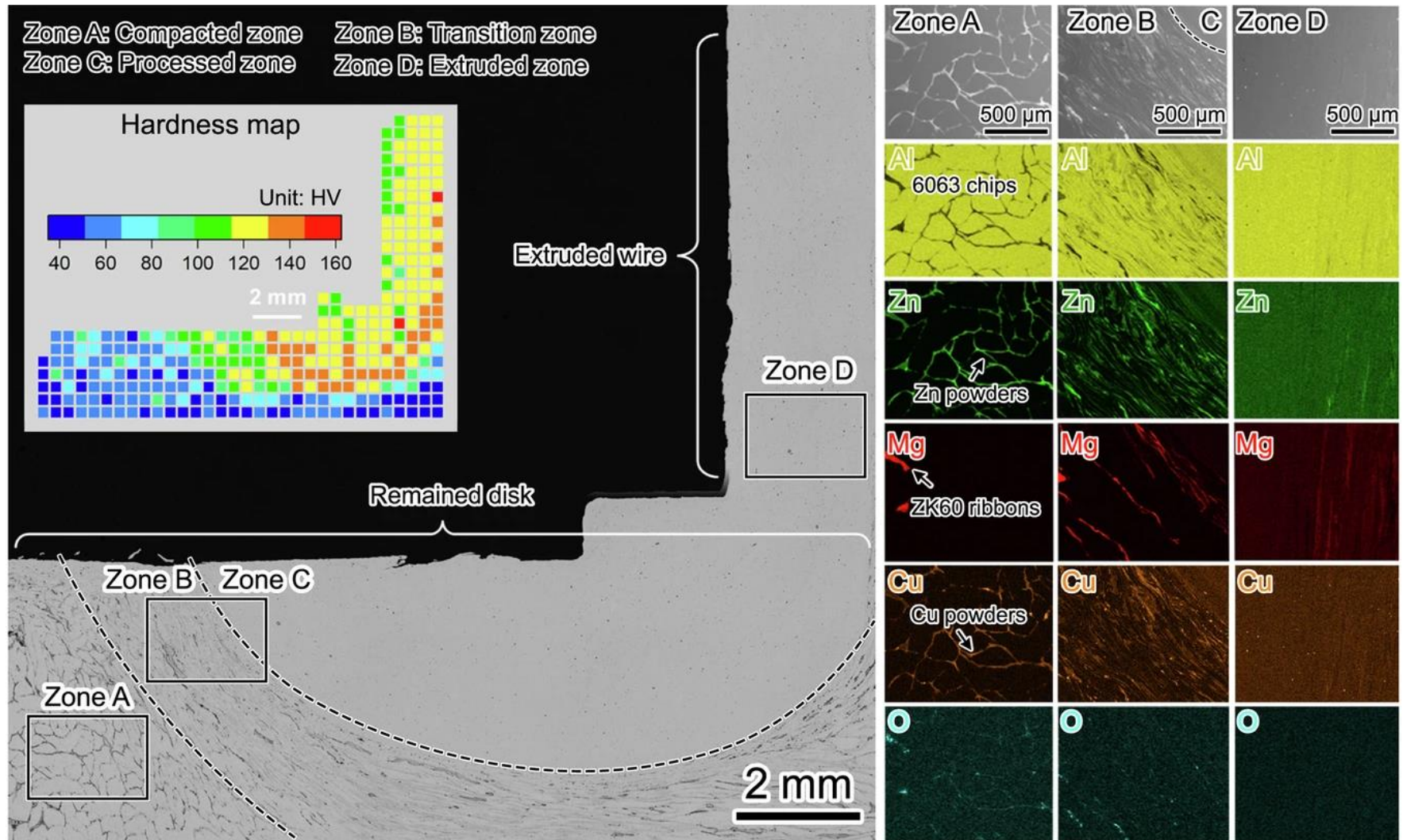
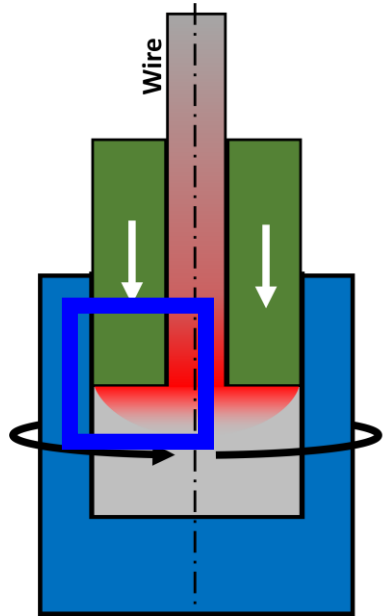


Friction Extrusion for Upcycling Materials



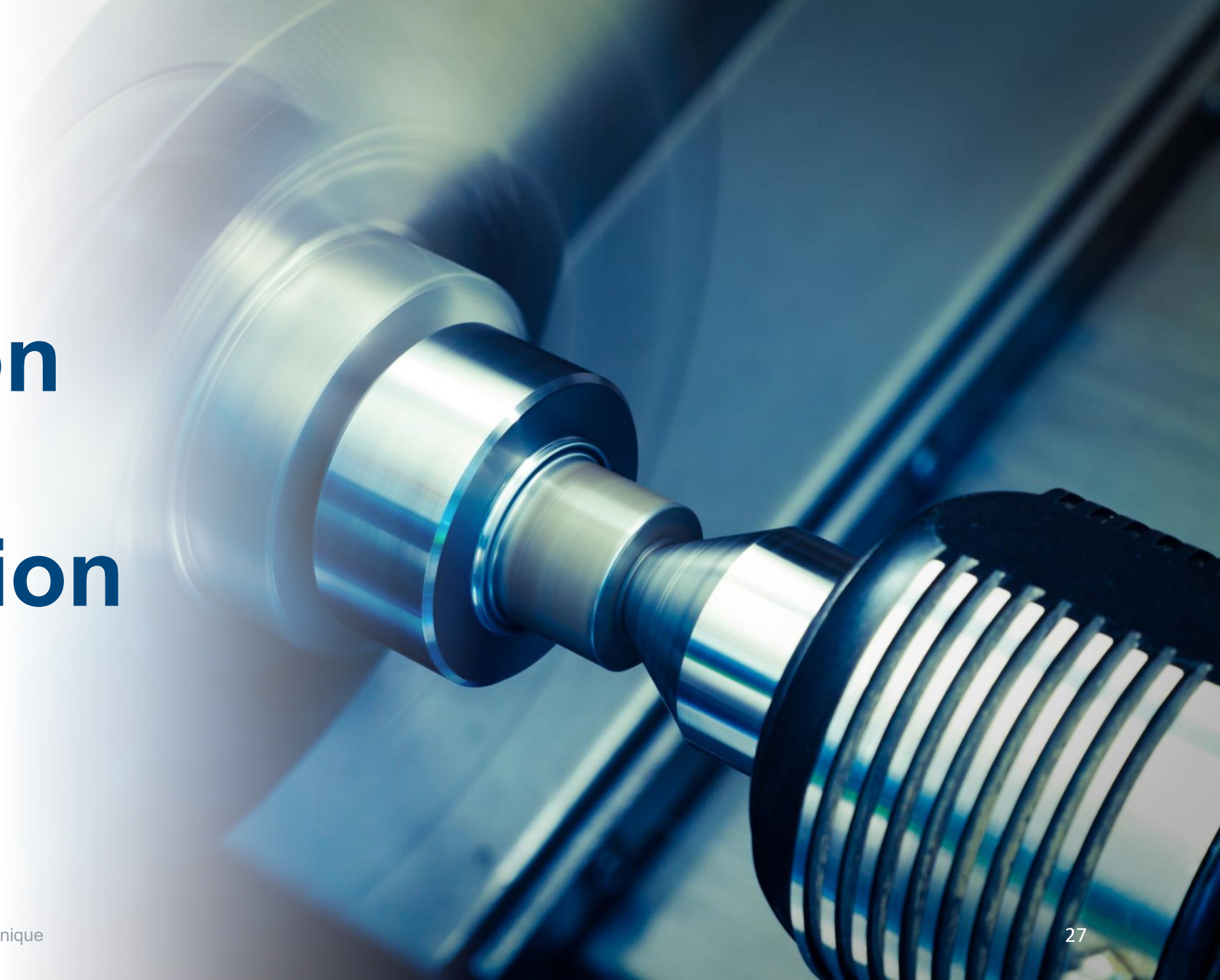
Wang, T., Li, X., Li, Z. *et al.* Upcycled high-strength aluminum alloys from scrap through solid-phase alloying. *Nat Commun* 15, 10664 (2024). <https://doi.org/10.1038/s41467-024-53062-2>

Friction Extrusion for Upcycling Materials

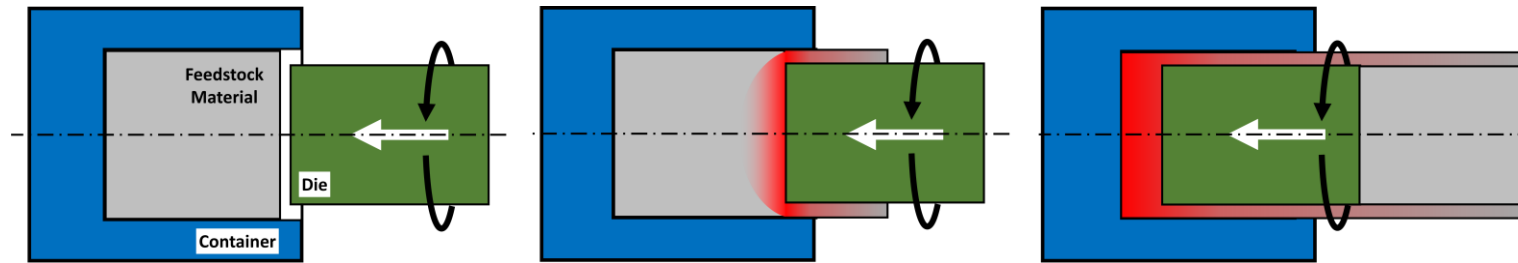


Wang, T., Li, X., Li, Z. *et al.* Upcycled high-strength aluminum alloys from scrap through solid-phase alloying. *Nat Commun* **15**, 10664 (2024).
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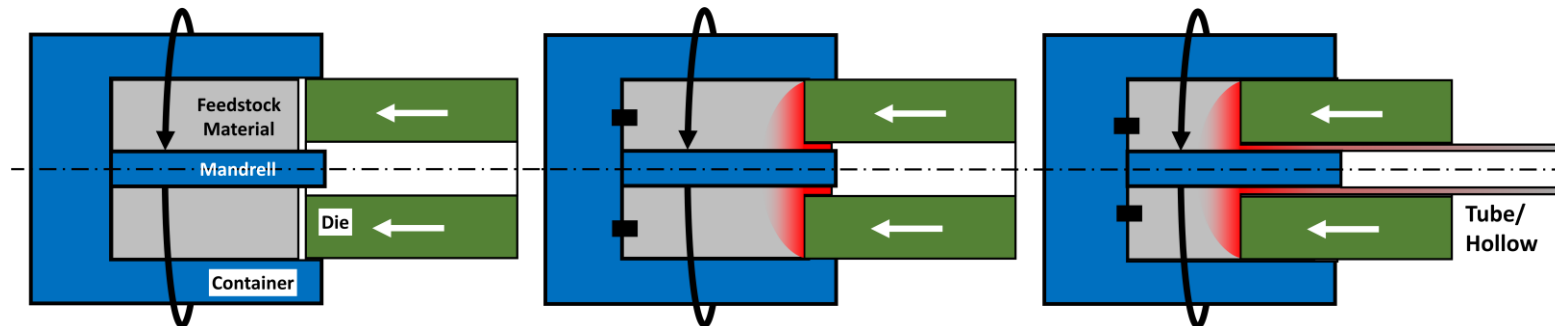
Friction Extrusion Tube Production



Friction Extrusion (Tube/hollow)

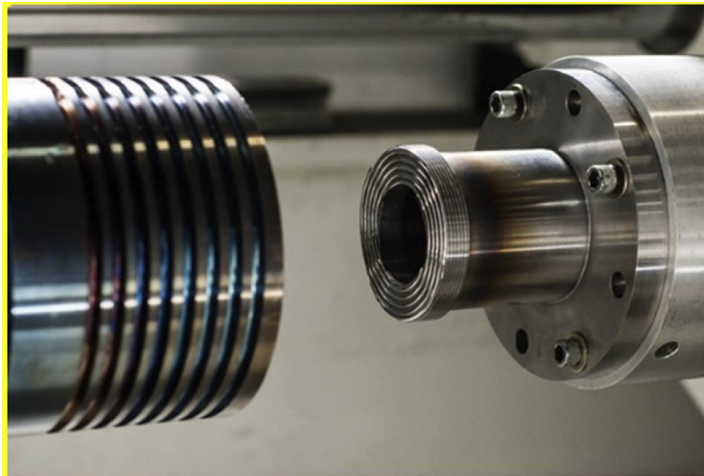
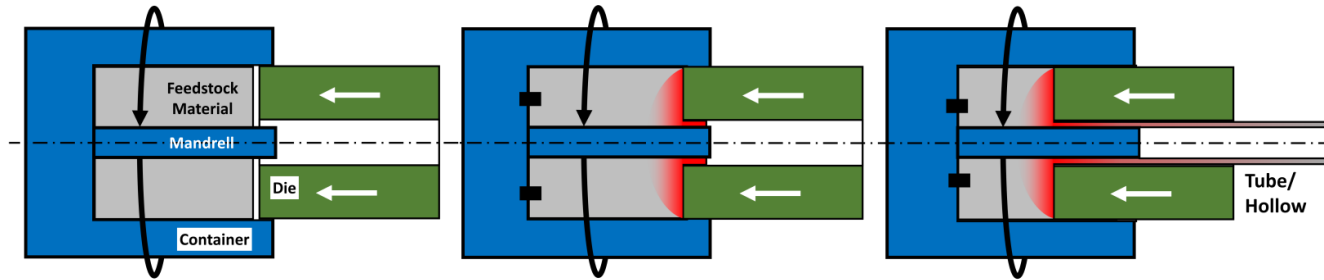


Friction Stir Back Extrusion

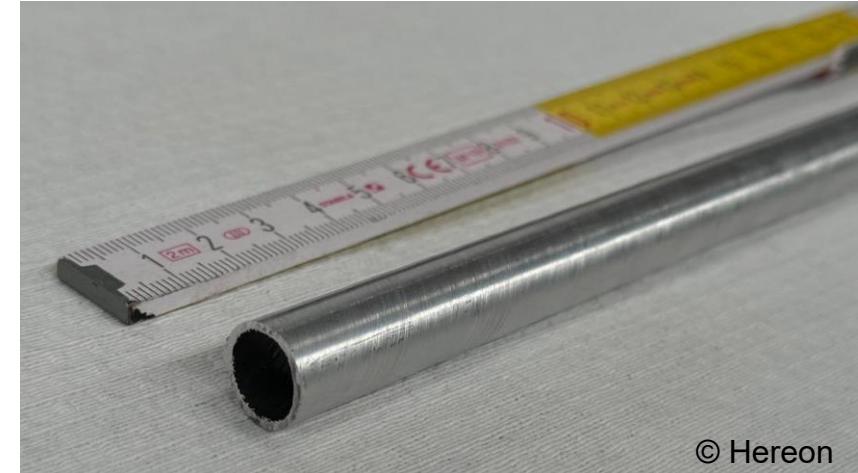


**Friction (Stir) Extrusion (FSE/FE) /
Shear-assisted Processing and Extrusion (ShAPE)**

Friction Extrusion (Tube/hollow)



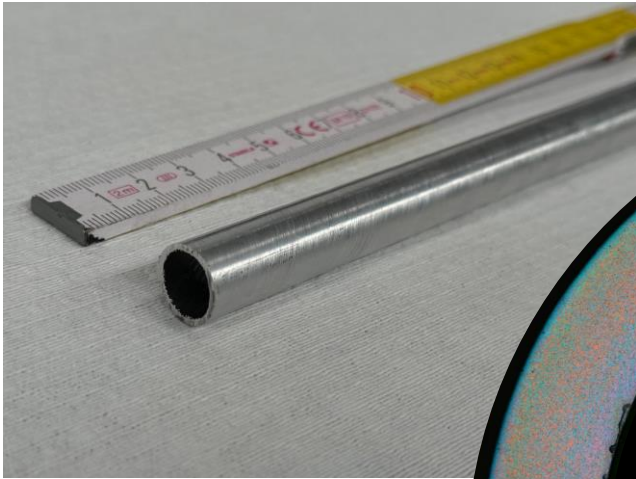
Al alloy AA6082



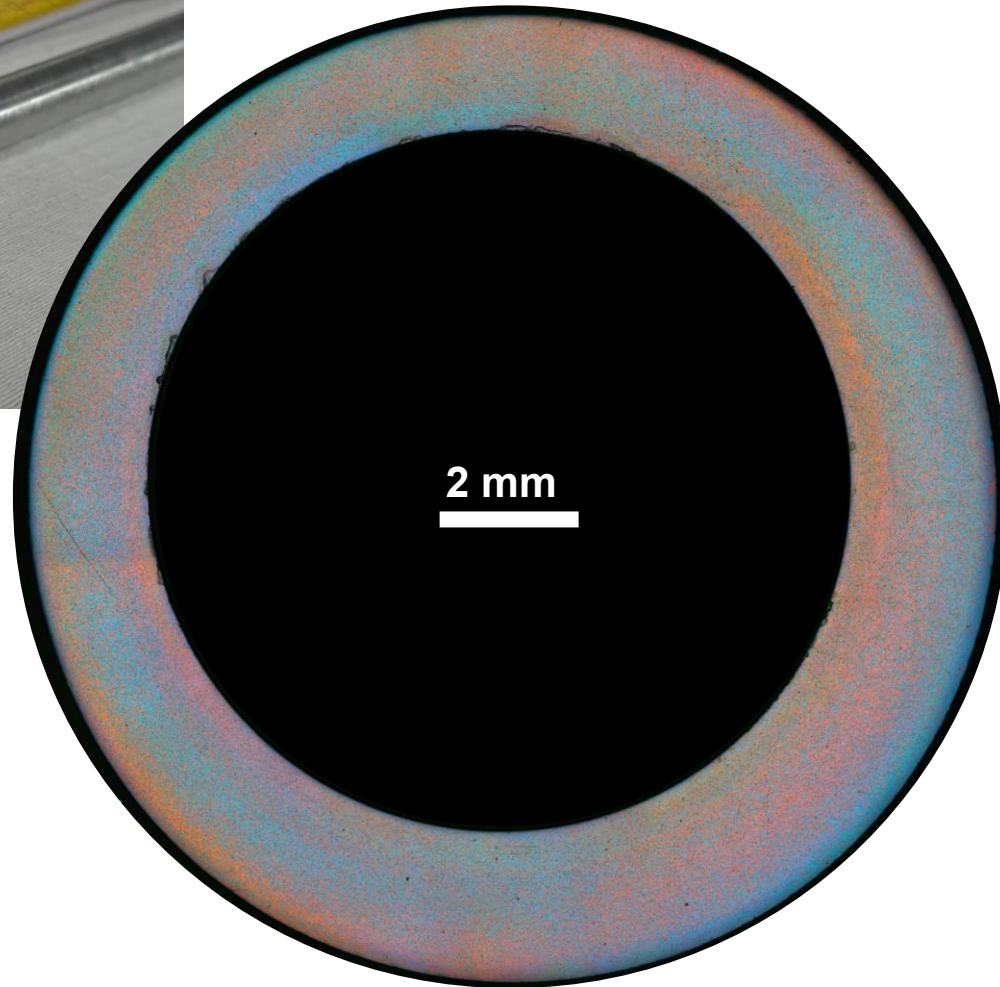
Mg alloy ZK60



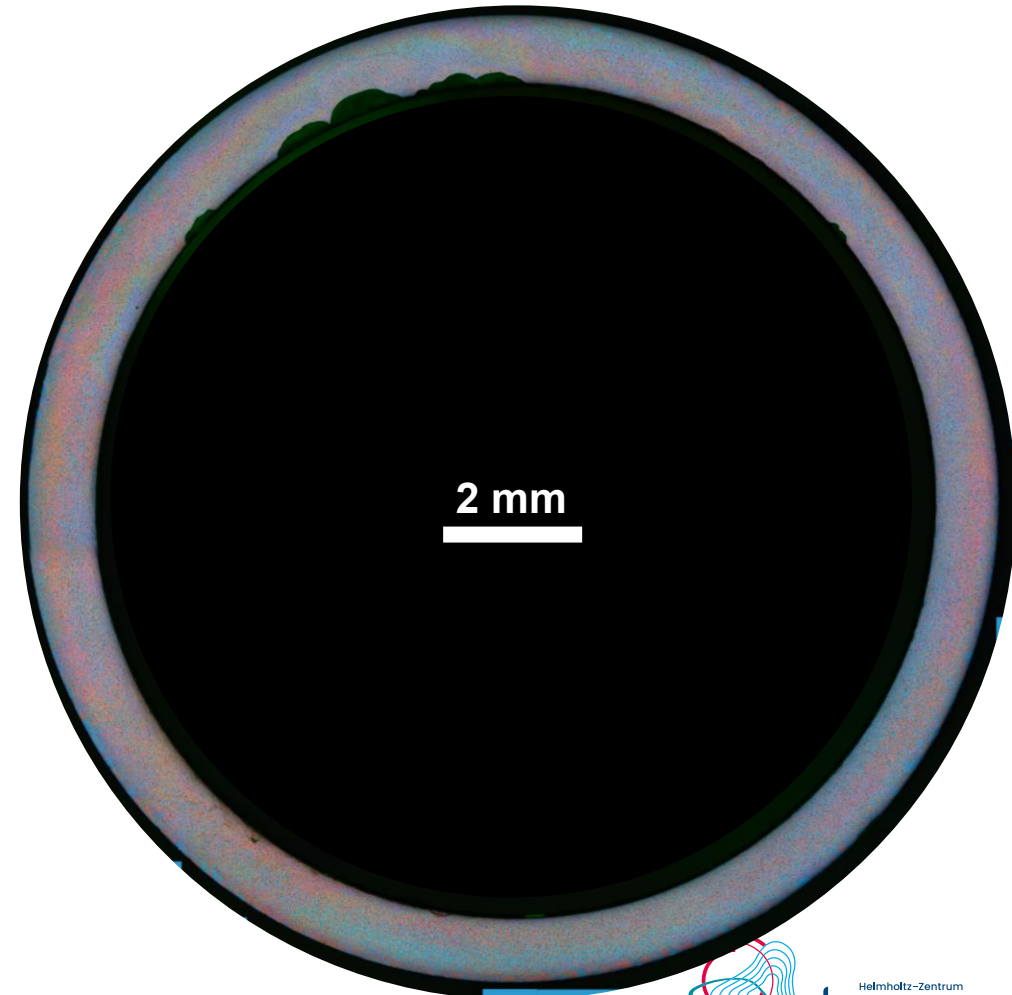
Friction (Tube) Extrusion



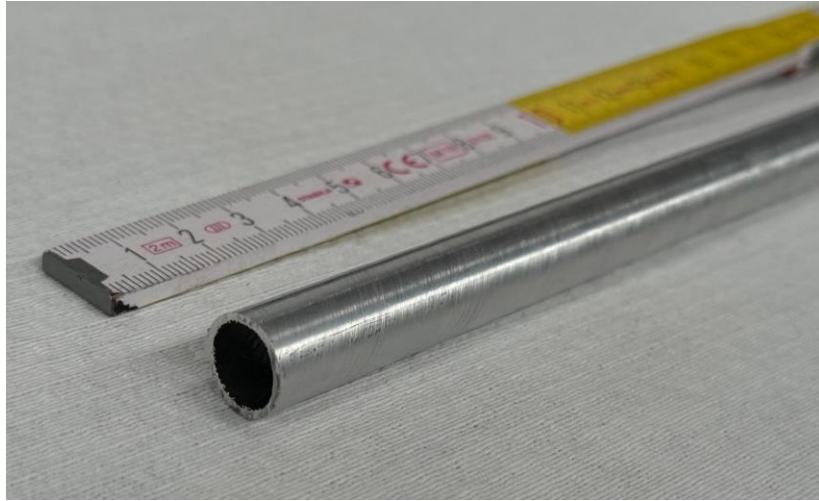
559: 14 – 10 mm diameter



560: 14 – 12 mm diameter

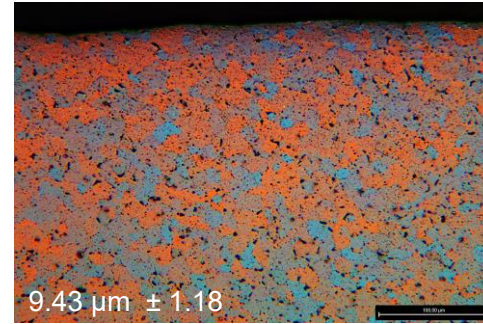


Friction (Tube) Extrusion



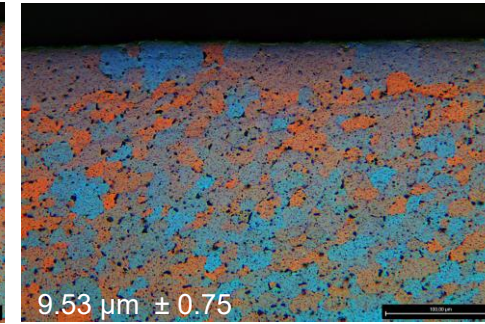
Outer Edge

First 175 mm

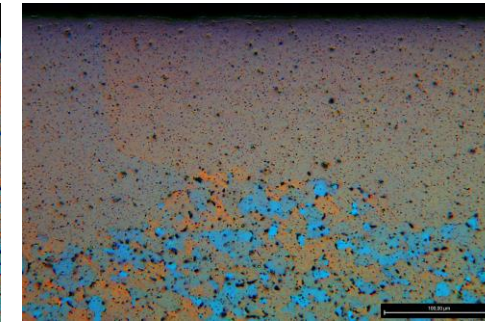


Longitudinal section

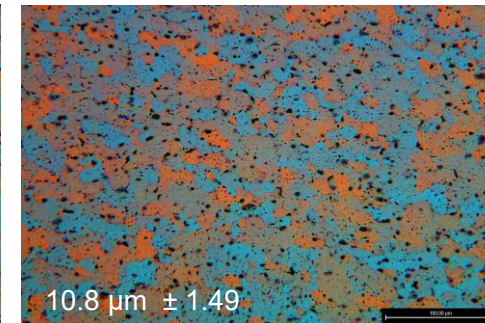
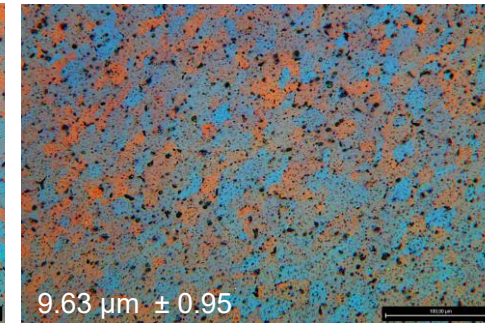
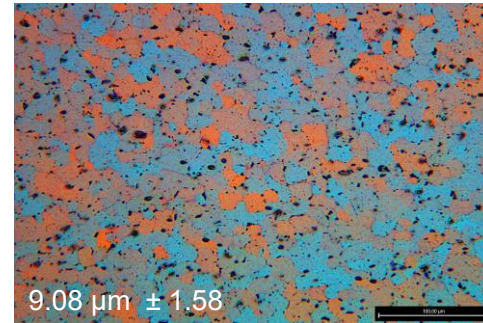
275 mm of extrusion



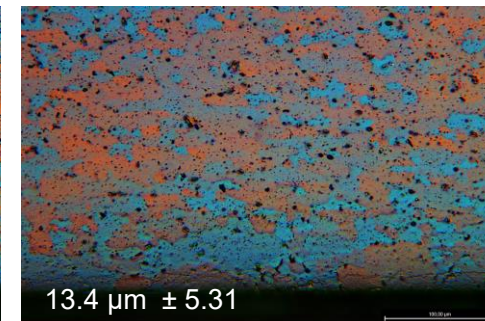
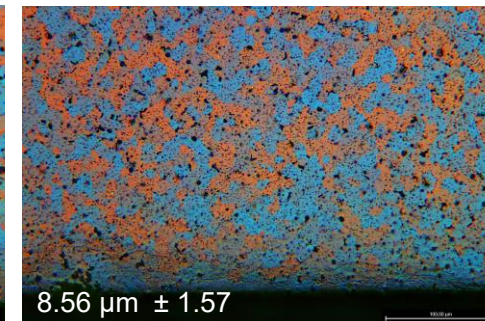
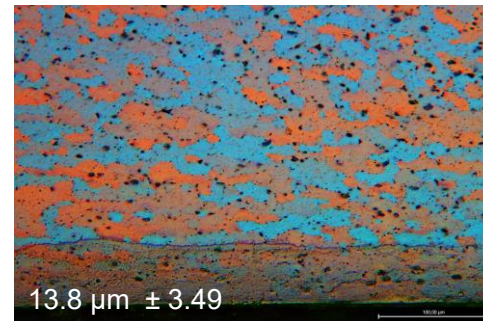
599 mm remaining



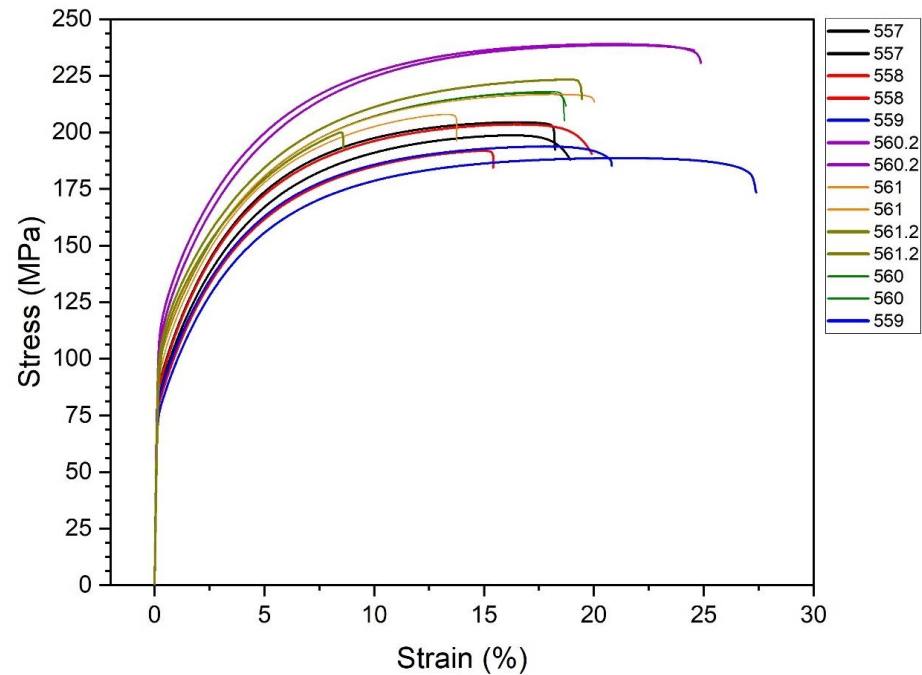
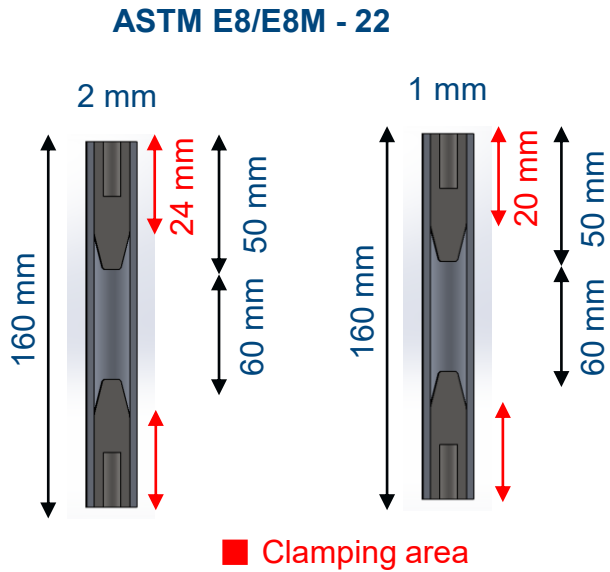
Middle



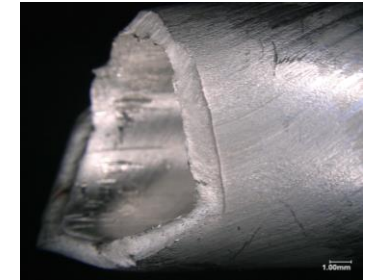
Inner Edge



Friction (Tube) Extrusion



Fracture surface



AA6082	Temper		
	O	T4	T6
Properties			
UTS (MPa)	130	205	290 – 310
YS (MPa)	60	110	250 – 260
Elongation at break (%)	27	14	10

Experiment	UTS (MPa)	Yield Strength (MPa)	Young Modulus (MPa)	Elongation (%)
557	203.5 ± 3.3	92 ± 2.2	64.5 ± 4.5	22.5 ± 2
558	197.8 ± 5.8	88 ± 4	63 ± 2.2	21.8 ± 0.2
559	191.4 ± 2.4	83.8 ± 3.7	61.5 ± 5.5	23 ± 1
560	228.2 ± 10.6	110.5 ± 6.5	60 ± 9	19.5 ± 2
561	212 ± 8.7	104.5 ± 8.7	59 ± 3	16 ± 3

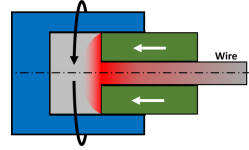
Friction Extrusion Mechanical Alloying

Mechanical alloying by FE process:

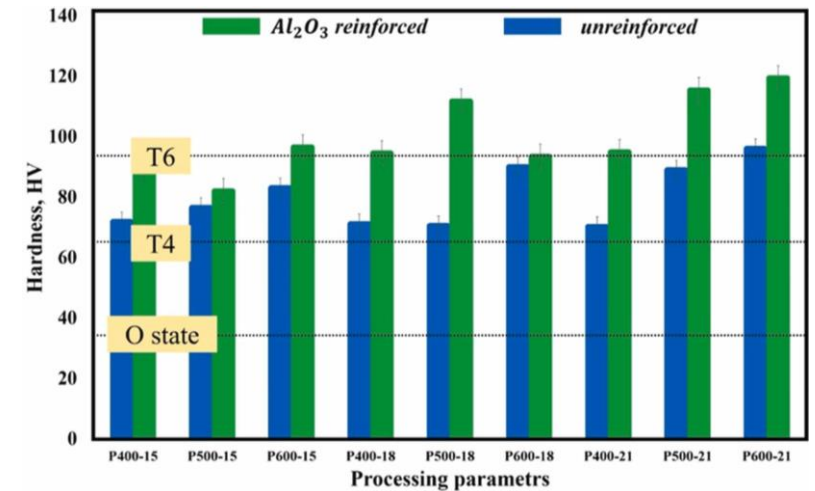
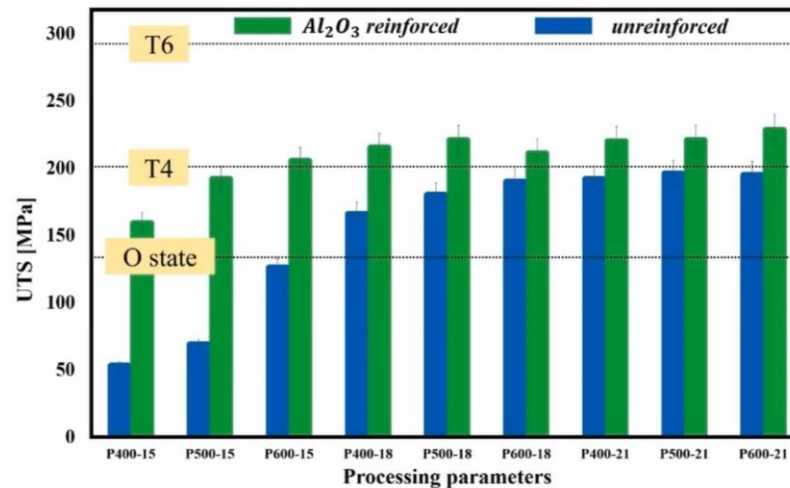
Manufacturing Aluminum Matrix Composite, ODS Al

6082 Al
scrap

+ 1% Al_2O_3



Oxide Dispersion Strengthened or
Aluminum Matrix Composite

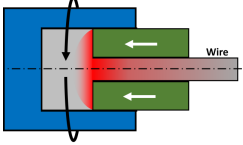


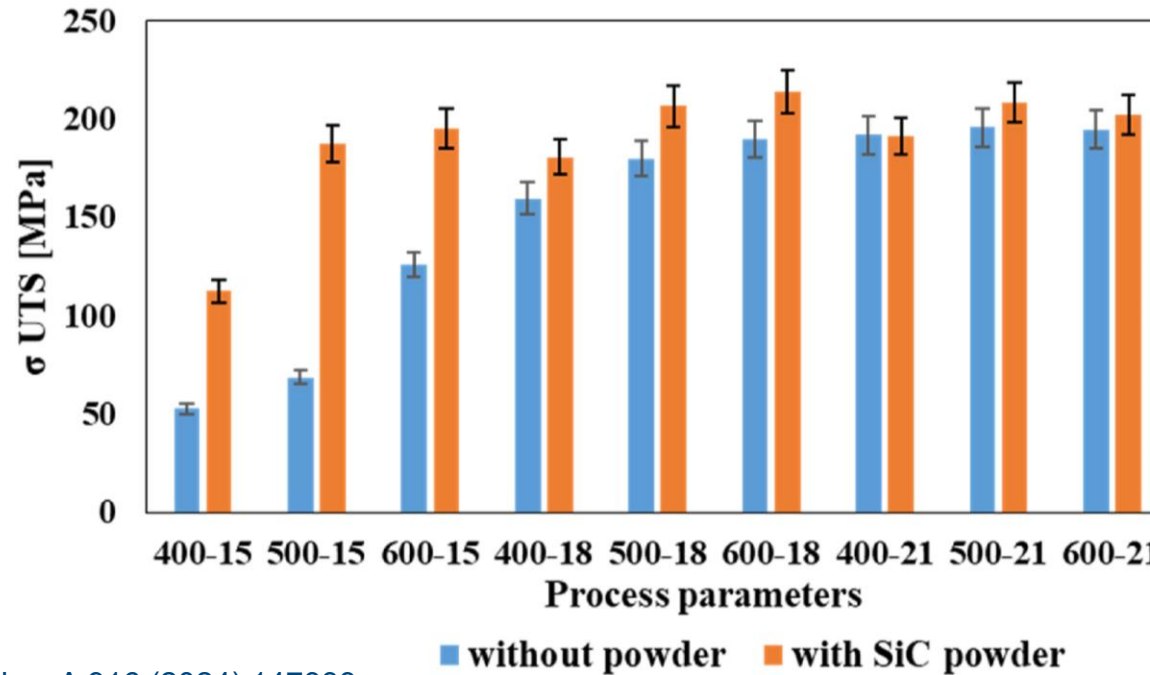
S. Emami et al, CIRP Journal of Manufacturing Science and Technology 61 (2025) 485-496
<https://doi.org/10.1016/j.cirpj.2025.07.006>

AA6082	Temper		
	O	T4	T6
UTS (MPa)	130	205	290 – 310
YS (MPa)	60	110	250 – 260
Elongation at break (%)	27	14	10

Mechanical alloying by FE process:

Manufacturing Aluminum Matrix Composite, ODS Al

6082 Al scrap + 12.5 % SiC →  → Aluminum Matrix Composite (AMC)



AA6082	Temper		
	O	T4	T6
Properties			
UTS (MPa)	130	205	290 – 310
YS (MPa)	60	110	250 – 260
Elongation at break (%)	27	14	10

M Adnan et al, Materials Science and Engineering: A 916 (2024) 147333
<https://doi.org/10.1016/j.msea.2024.147333>

Summary

Friction Extrusion and process variant is an energy efficient process utilizing friction between the non-consumable tool and feedstock material to generate severe plastic deformation and frictional heating.

FE and its variant can be utilized for:

1. **Processing various feedstocks** (solid, chips and powder) into solid and hollow extrudates.
2. **Recycling end-of-life materials** into valuable products with the same composition.
3. **Upcycling end-of-life materials** into higher-grade materials.
4. **Mechanical alloying** of materials with strengthening particles.

Thank you for your attention!

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