Break through - Upscaling Recycling Alloys with Ultrasonic Melt Treatment

When I saw the first tensile test results from ultrasonically treated castings presented to me, I had the feeling. “*This going to make waves in the foundry industry*".

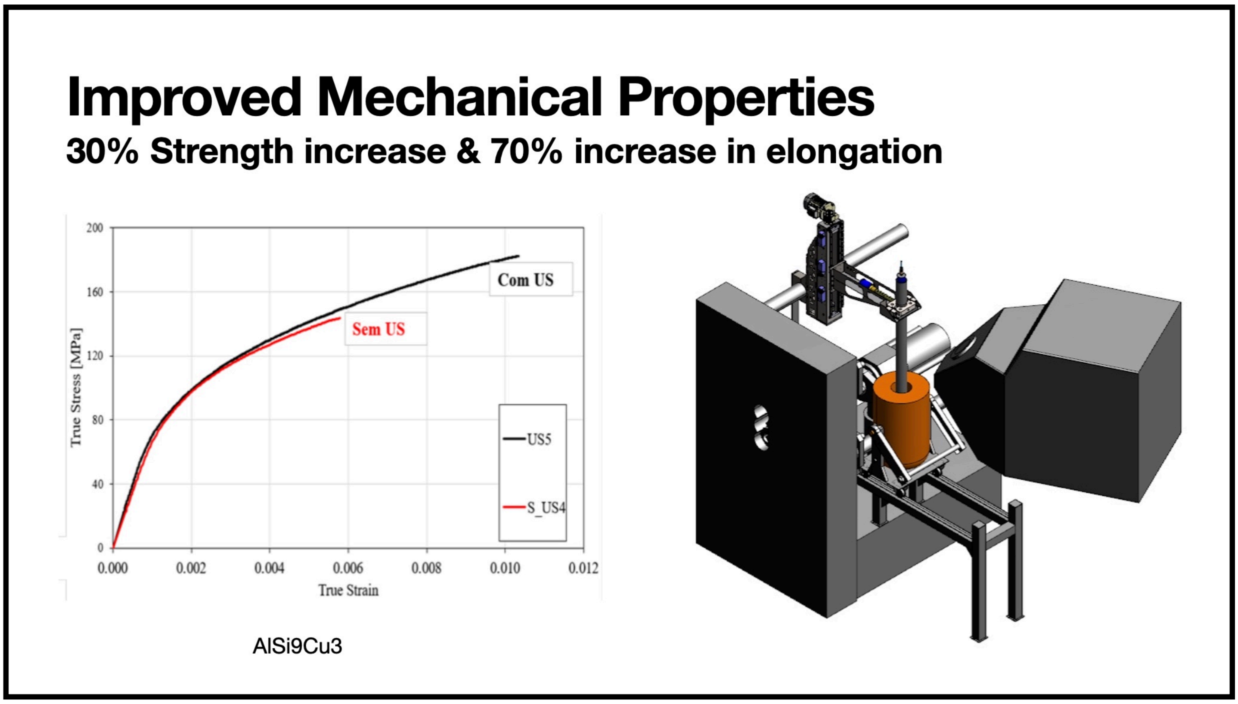


Fig. 1 - MMM-Ultrasound in HPDC foundry (courtesy MPI-Ultrasonics)

Material circularity

Aluminium recycling is a large contributor to the circular economy. 75% of all aluminium ever made is still in use. However to maximise the value of the recycled aluminium, we still have a few challenges.
Structural castings still need a substantial amount of primary aluminium to obtain the properties required for the various parts. To meet the strength levels often a T6-temper is needed, and the quench after solution heat treatment create distortion in the casting, as well as additional costs. If we would have excess elongation in the as-cast condition, we could substitute this for strength during artificial ageing in a T5-temper.

The bulk of the aluminium obtained from End of Life Vehicles (ELV) is actually down cycled and ends up in secondary foundry alloys A380 and ADC12 (A383).

To improve the situation several approaches are used:

1) *Sorting technologies*: Xray diffraction and LIBS to sort aluminium by alloy families
2) *Design for disassembly & uni-alloy design by OEMS:* to ease the alloy segregation at end of life.
3) *Purification technology:* fractional solidification to takeout unwanted elements from the melt

….we now introduce a fourth route.

4) *MMM*-Ultrasonic metal treatment:* grain refinement and fragmentation and shape of intermetallics to make them less harmful and increase casting ductility.

Most likely the ultimately solution for material circularity will be a combination of the points listed above.

Note (*) MMM stands for multi-frequency, multi-mode, modulated ultrasound and was introduced by MPI-ultrasonics in 2002.

Ultrasonic intermetallic modification has been studied for several decades [3]. However it takes a robust industrial process and a large amount of casting trials to develop the processing conditions to repetitively obtain homogeneous mechanical properties in casting recycling alloys.

Recycling alloys and intermetallics

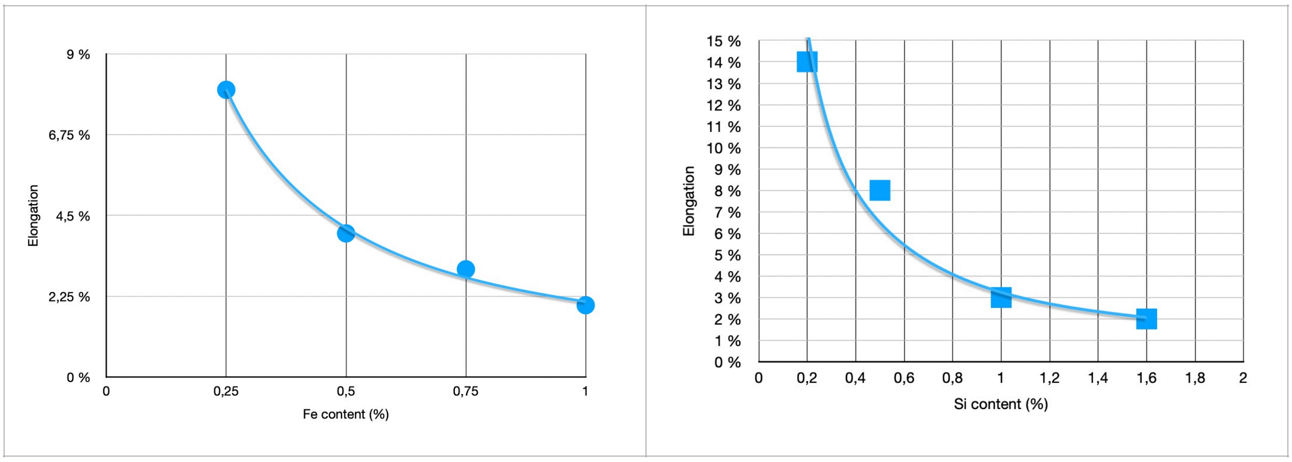
The aluminium section of recycled ELVs is called "Twitch". It is a mixture of cast and wrought alloys and typical chemical composition is shown here:

	Si	Fe	Cu	Mn	Mg	Zn
Twitch	5 %	0.5%	1.5%	0.2%	0.7%	0.8%
A380	8 %	0.8%	3.4%	0.2%	0.1%	2.2%

Table 1 - Main alloying elements of Twitch and A380

How to make structural castings from this metal?

The main problem with this type of metal is the ease to fracture caused by the brittleness of the casting. Elongation is seldom more than 1 - 2%, which is unacceptable in a structural casting. The brittleness is caused by "platelet-like" shaped intermetallics, which form in the inter granular spaces of the microstructure during solidification.
The relationship between these intermetallics and ductility is shown below. The graphs show the drop in elongation due to the intermetallic formation when iron (Fe) is added to Al-Si alloys (left) and when silicon (Si) is added to Al-Mg alloys (right).



Al-Si type alloys: A356 (AlSi7Mg). Best elongation is obtained at low iron (Fe) levels, when little β Al5FeSi is formed. Many studies have confirmed 0.25% to be the maximum tolerable Fe-content for structural parts. At higher Fe levels, β-Al5FeSi phases form throughout the microstructure and elongation drops rapidly from 8% to 2%. This β-phase displays this typical platelet like structure (s. figure 2).

Al-Mg type alloys: A study with Castaduct 42 (Rheinfelden) Al4Mg2Fe shows that silicon becomes a problem. When Si-levels increase above 0.2% the intermetallic Al13Fe4 dominates

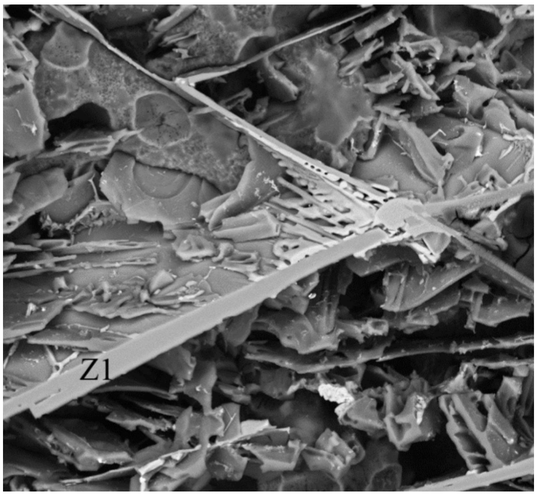


Fig.2 - β Al5FeSi platelets in A356

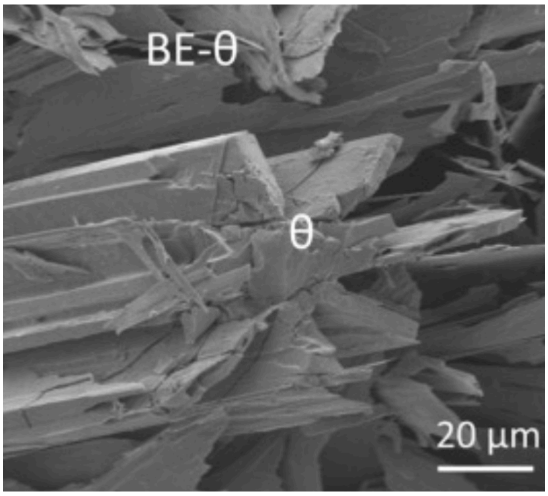


Fig.3 - Al13Fe4 platelets in Castaduct 42

and increases in seize, resulting in a drastic drop in elongation. The shape of Al13Fe4 is shown in Figure 3.
Castaduct 42 already is a recycling friendly alloy due to its high Fe-content (2%). Up to 75% recycled content can be used in this high pressure die casting alloy.

Acoustic Cavitation in liquid Aluminium

Figure 4 shows the principles of acoustics cavitation. When ultrasound is applied to liquid metal, the peaks of an ultrasonic wave result in compression, and expansion of bubbles and gas in the melt. This eventually leads to bubble collapse and creates hydraulic shockwaves with local pressures of thousands of MPa and local temperatures of up to 5000^{0}C [1].

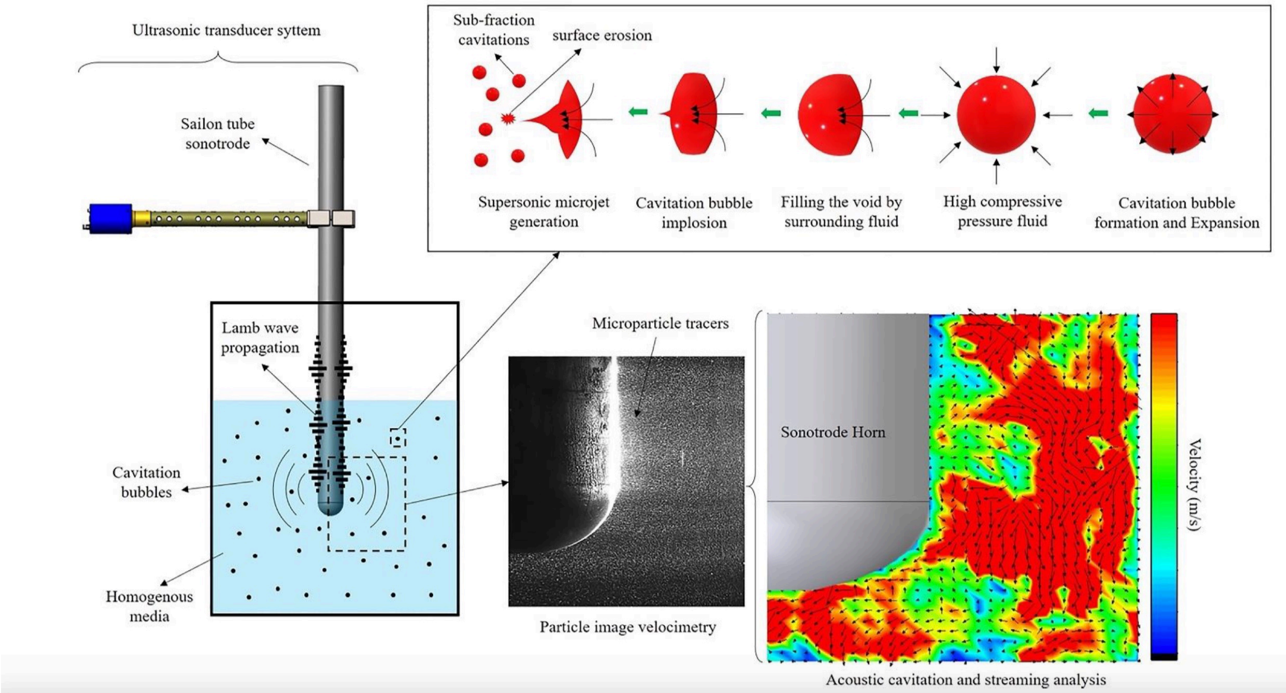


Fig. 4 - MMM-Ultrasonic treatment (courtesy MPI-ultrasonics)

This process of ultrasonic agitation and acoustic streaming create shock waves and increase mass transport due to the turbulence of cavitation. The sonication process has several effects in aluminium and the dominant effect depends on the metal temperature during sonication:
1) Degassing
2) Grain refinement
3) Intermetallic modification
4) Enhanced fluid flow during mould filling

At high temperatures above the liquidus, primarily degassing occurs by rising cavitation bubbles bringing soluble hydrogen to the surface.
The MMM-Ultrasound creates cavitation homogeneously throughout the melt. During expansion, bubbles absorb energy in the melt, undercooling the liquid at the bubble-liquid interface, resulting in nucleation on the bubble surface. When bubbles collapse acoustic streaming develops in the melt, distributing the nuclei into the surrounding liquid producing a significant number of nuclei in the molten alloy, thus promoting heterogeneous nucleation (in-situ grain refinement).
The cavitation also alters the formation and the morphology of the first solidifying phases and causes fragmentation of oxides, which operate as nucleation sites.
Finally the shape and size of intermetallics is modified due to the ultrasonic energy injected into the melt [3].

Ultrasonic treatment of A380

The effects of US-treatment are temperature dependent and grain refinement and intermetallic modification is most pronounced at temperatures slightly above the liquidus temperature.
For A380 we obtained the best results at 620°C, which is 17° above the liquidus temperature of this alloy (603°C).

Three types of intermetallics are present in the alloy and they crystallise at particular temperature intervals, which are well below the sonication temperature:
- β-Al5FeSi (570-582°C)
- α-Al15(Fe,Mn)3Si2 (560-566°C)
- CuAl2 (492-509ºC).

We obtained grain refinement from average 30 micron down to 20 micron.
Figure 5 and 6 show the intermetallic modification from platelet to small polyhedral shapes.

One hypothesis of the intermetallic modification is the lack of intergranular space. Due to the ultrasonic grain refinement a very large number of globular α-Al grains form, which leave little room for the intermetallic phases to grow large.

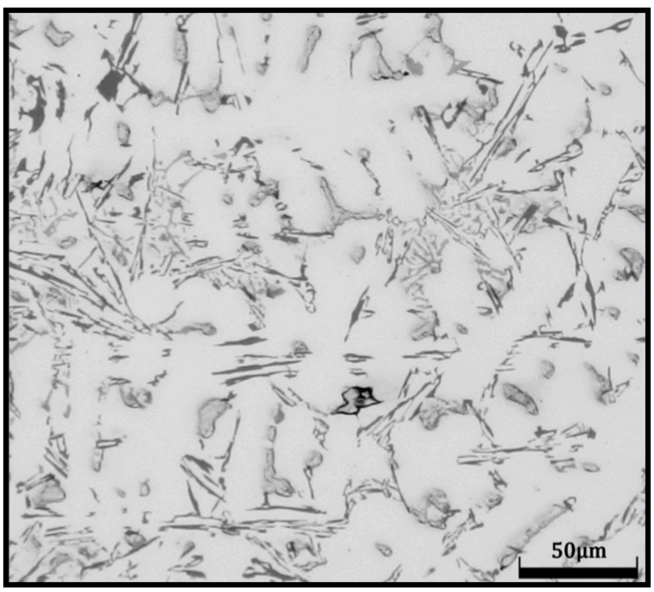


Fig. 5 - untreated A380

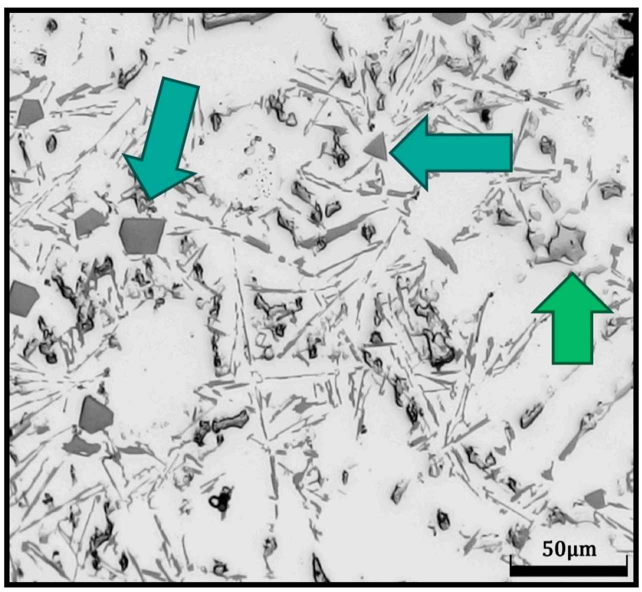


Fig. 6 - US treated A380

The other hypothesis is that the hydraulic pressure in the metal leads to dense polyhedral or block size intermetallic formation, which would normally be platelet-like in untreated metal.

Pilot casting trials in A380 in HPDC

The industrial set-up and the equipment used in the foundry is shown in figure 7.

Fig. 7 - Industrial set-up MMM-Ultrasonic Treatment in Foundry

In between the casting furnace and the shot sleeve a 20 kg container is used for MMM-Ultrasonic treatment. The US-treatment occurs during the casting cycle. After sonication the metal is poured into the shot sleeve, and the container is refilled for the next cycle.
For pilot casting a standard part was chosen and tensile properties were taken form three different positions.

To get a full understanding of ultrasonic effects on the mechanical properties, ultrasonic treatment was done at different temperatures from 700 °C down to 620 °C. It shows that maximum increase of tensile strength and elongation occurs at the lowest temperature.
We obtained consistent best results with temperature 625°C +/- 5°C. Table 2 shows the mechanical properties in the as-cast condition.
The values are averaged over the three locations.

For consistent mechanical properties the following parameter control is required:
- Melt temperature during sonication
- Sonication time
- Time between sonication and casting
- Ultrasonic generator settings
- Sonotrode position (depth) in the melt

The foundry practice confirms the metallurgical results obtained and studied in the lab. The sonication process is robust and can be applied to any kind of casting process.

	UTS (MPa)	Elongation (%)
No US treatment	143	0.58
UST @ 700°C	149	0.65
UST @ 680°C	153	0.72
UST @ 660°C	160	0.80
UST @ 640°C	173	0.95
UST @ 620°C	181	1.12

Table 2 - Mechanical properties - A380

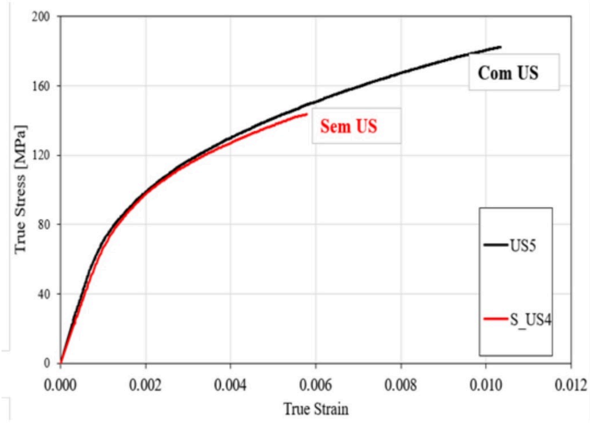


Fig. 8 True stress strain curves - A380 (US @ 620°C)

Making structural castings with 100% recycling alloys

Next trails should be done with several types of aluminium-silicon and aluminium-magnesium alloys with various scrap concentrations. A structural casting should be used and apart from mechanical testing and microstructural analysis, we shall conduct crash tests and as well as riveting tests.

Fig. 9 - Post consumer scrap

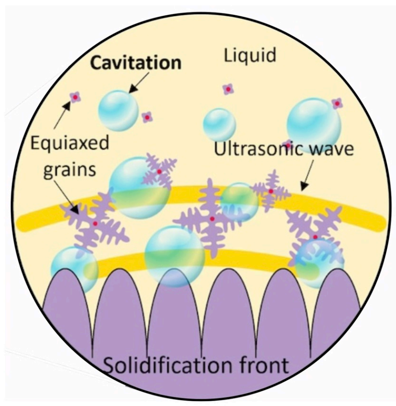


Fig. 10 - Ultrasonic schematics

Accelerated mould filling of Giga Castings - new project

Apart from microstructural advantages, the fluid flow enhancement of aluminium through MMMultrasonic treatment has hardly been studied until now. The ultrasonic agitation leads to increased mass transport during casting. The “energised” metal displays an improved fluidity, which increases flow length before solidification. This is very useful in Giga casting where long flow lengths are one of the challenges.

Fig. 11 - Spiral mould fluidity test

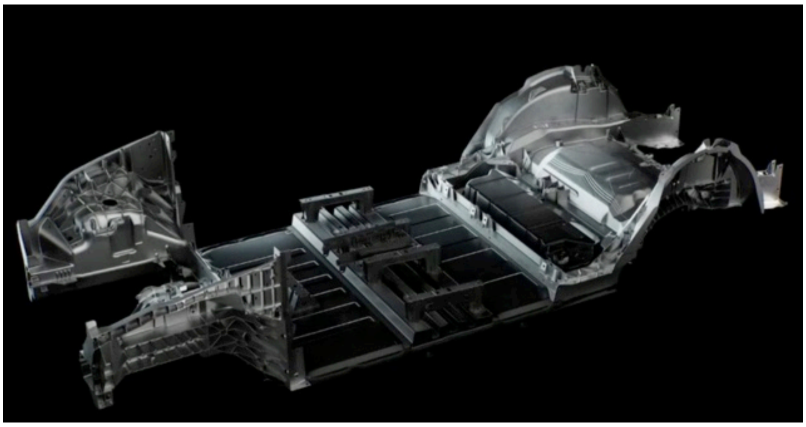


Fig. 12 - Giga castings

A new project should be planned to investigate this phenomenon in full detail and test in an industrial environment.

MV/17.7.2024

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[2] R.F. Jaime, H. Puga, D. Apelian, *Fundamentals of Ultrasonic Treatment of Aluminum Alloys* (2024) American Foundry Society (2024).

[3] H. Puga, S. Costa, J. Barbosa, M. Prokic, *Influence of Ultrasonic Melt Treatment on Microstructure and Mechanical Properties of AlSi9Cu3 Alloy*

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[5] N. Unal, H. E. Camurlu, *The effect of ultrasonic treatment during casting of a hypereutectic Al–Si alloy,* International Journal of Cast Metals Research (2012) Vol. 25 No 4 246-250