

[www.UltrasonicMetallurgy.com](http://www.UltrasonicMetallurgy.com)

# Ultrasonic vibrations in metallurgy...

Technology, results, difficulties...

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# Summary

## Part 1

### History of Ultrasonic Processing in Metallurgy – Ultrasonic Treatment of Light Alloy Melts

#### Theoretical foundations

- Cavitation, temperature, amplitude, frequency...

#### Reality & Practice

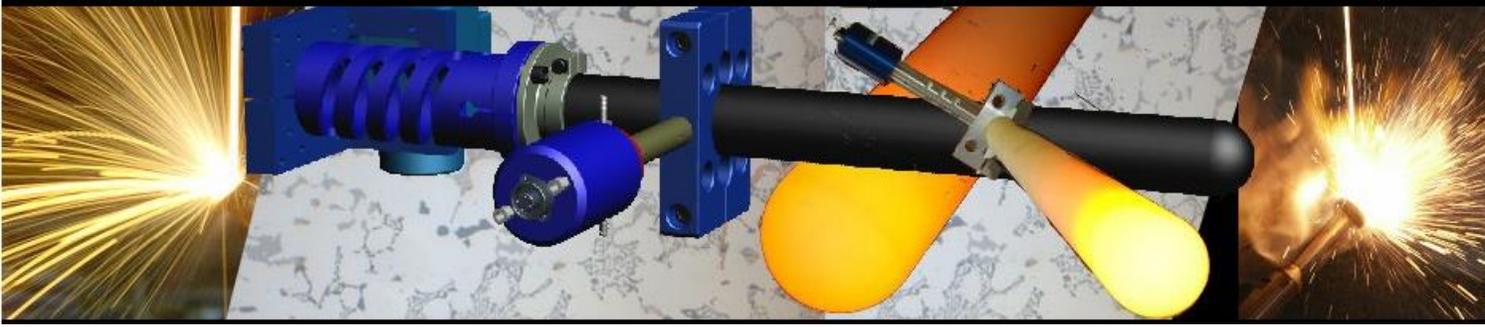
- How can I control the process?
  - Can I control the process with my equipment?
  - What the best characteristics of “*Ultrasonic Activity*” are?
  - Design solutions applied in treatment of Light Alloy Melts
- ✓ Results of MMM technology applied in processing of aluminum alloys

## Part 2

Some ideas/proposals

## Part 3

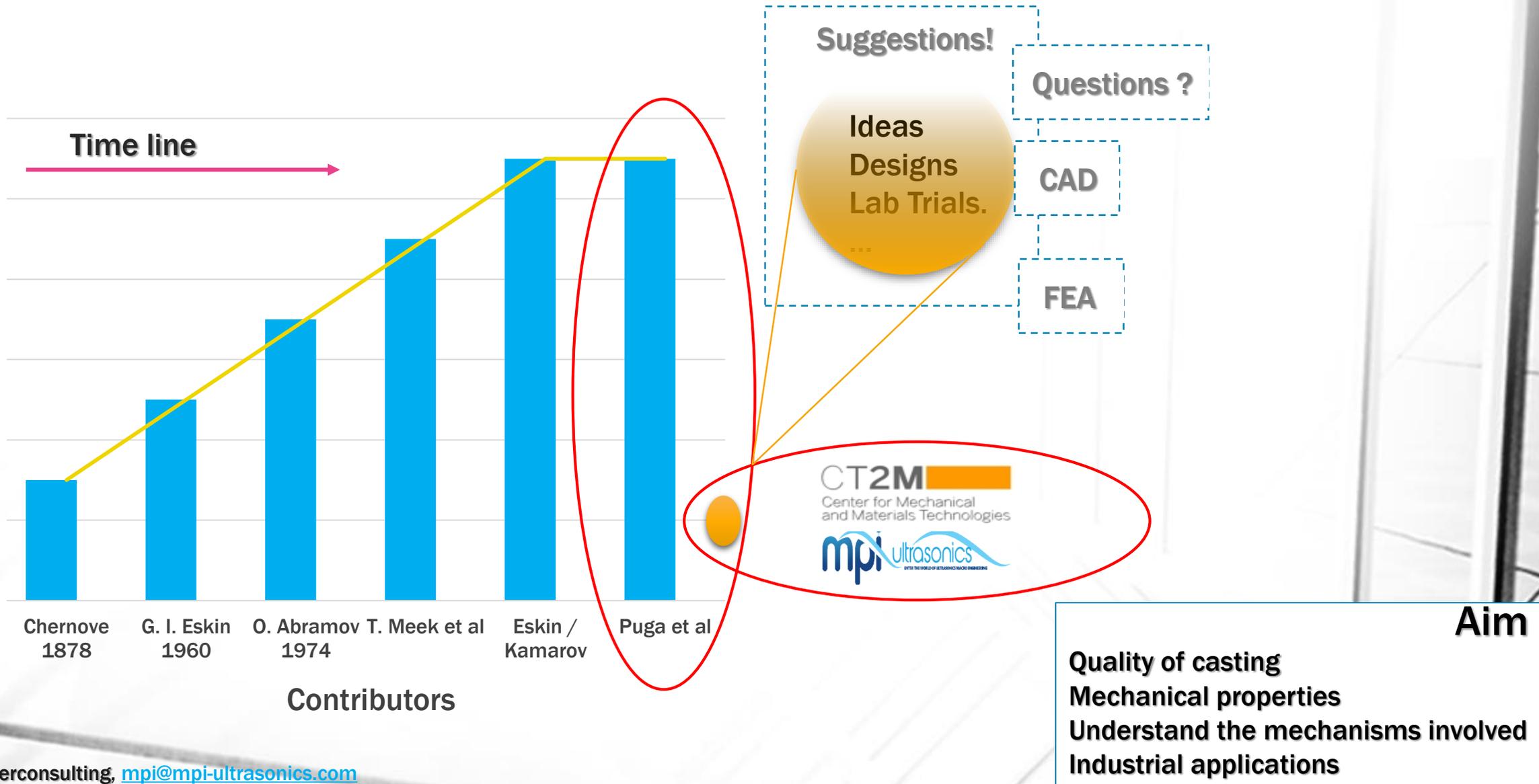
How can I control the cavitation?



# Ultrasonic vibrations in metallurgy...

**Part 1**

# History of Ultrasonic Processing in Metallurgy – Ultrasonic Treatment of Light Alloy Melts



# History of Ultrasonic Processing in Metallurgy – Ultrasonic Treatment of Light Alloy Melts

What the differences between us and Others are?

## Fixed frequency sound waves

Others

Standing waves break ceramic sonotrodes, while creating spatial zones of very high and very low acoustic activity.

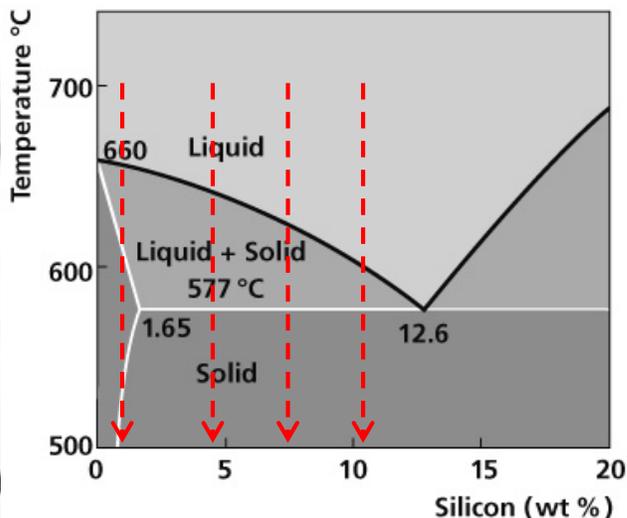
MMM (=) Multi-frequency, Multi-Mode, Modulated sound waves.

we

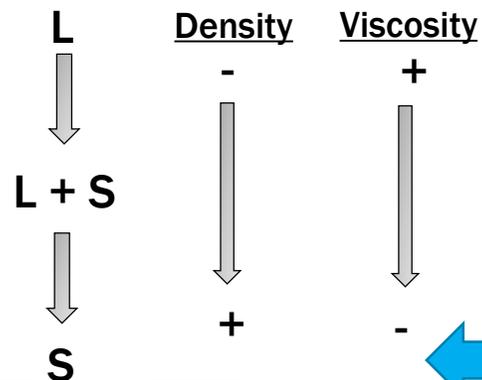
Multi-frequency, pulse-repetitive, frequency, phase and amplitude modulated, bulk-wave excitation.

Elimination of ultrasonic standing waves gives spatially uniform processing of liquid metals.

Capability to drive ultrasonically any arbitrary solid body shape, or large mechanical system at high energy, if needed.



... State change ...

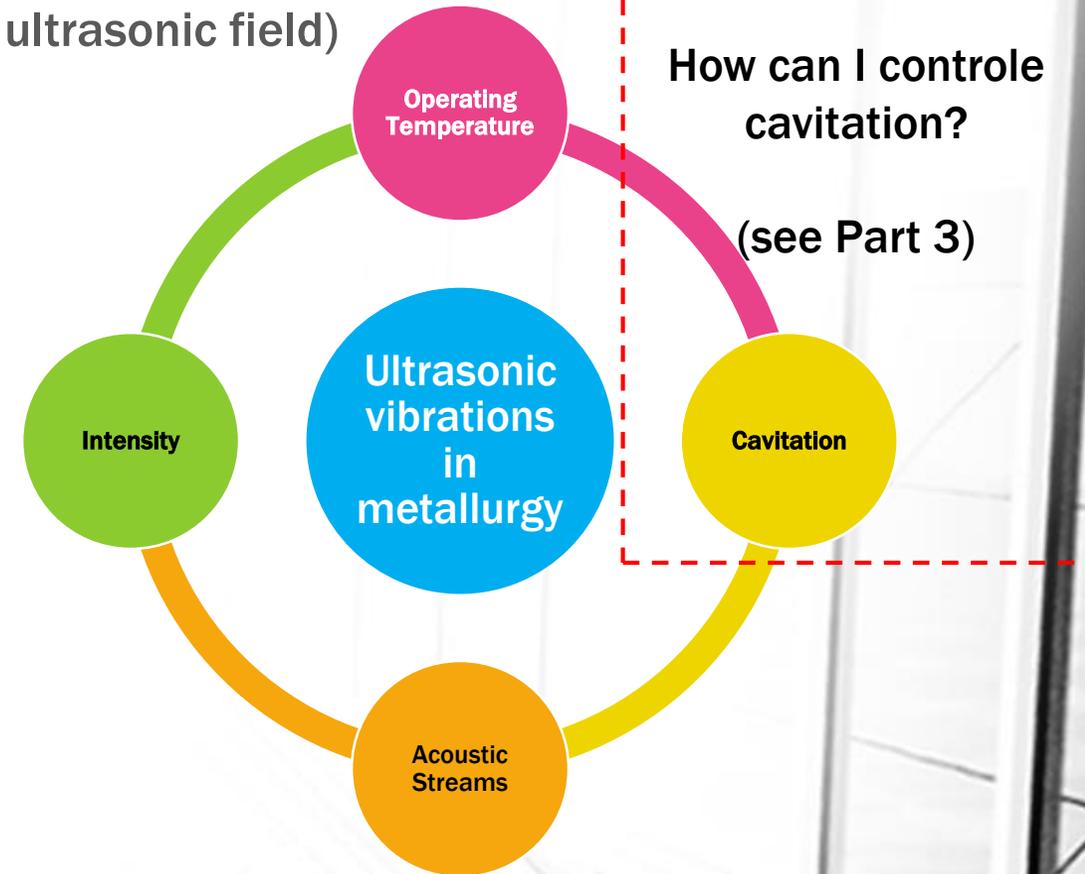
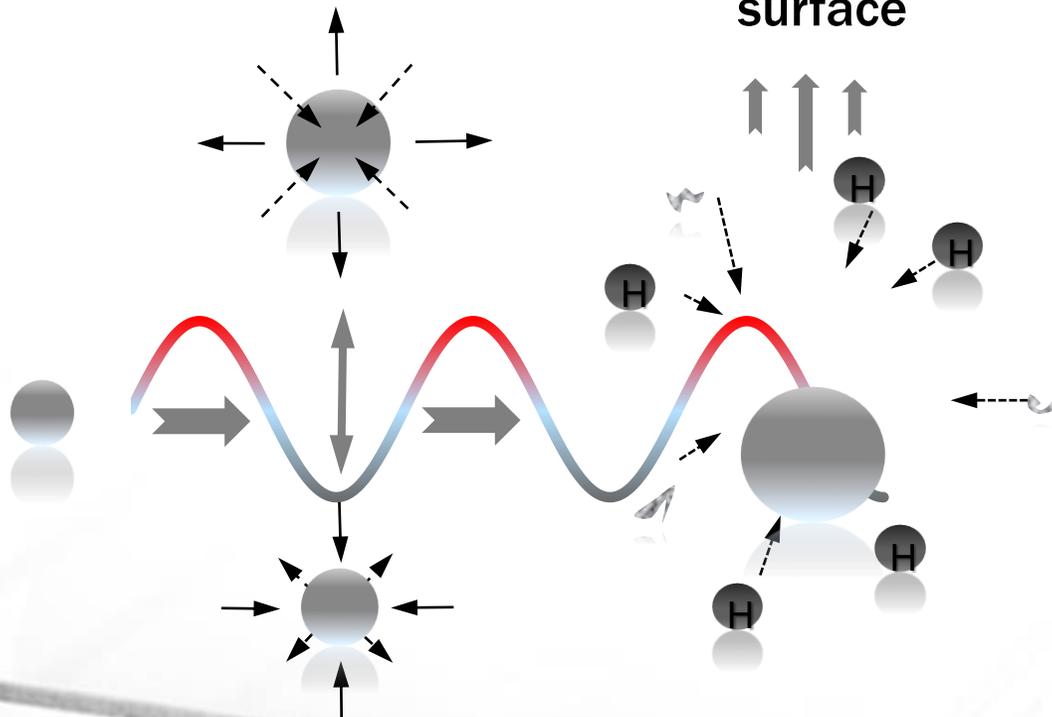


To solve:  
Multifrequency, Multimode, Modulated sound waves.

# Theoretical foundations

- Cavitation – consequence of an external action (in this case ultrasonic field)
- Acoustic streaming

$$I = \frac{P}{S} \left( \frac{W}{cm^2} \right)$$



# Theoretical foundations

## Advantages of Acoustic Processing

- Grain refinement with significantly improved and 3D uniformly distributed micro-crystallization.
- Disintegration, elimination, wetting and dissolving of non-metallic and metallic inclusions, making smooth intermetallic transitional areas.
- Alloys mixing with nano-particles, increasing density of alloys, varying percentages of alloy ingredients.
- Improving chemical, mechanical and physical properties and corrosion resistance, e.g. in Al-Li alloys and other aerospace alloys.
- Alloys' density increase until theoretical limits.

# Theoretical foundations - Continuous and Static Casting with Ultrasound

## Degassing

### Principle:

Supplying acoustic energy to a melt, in order to induce cavitation and initiate Sonocrystallization:

- (i) A great number of small cavities developed inside the liquid.
- (ii) Diffusion of hydrogen from the melt to developed bubbles
- (iii) Large bubbles coagulate and float to a surface of liquid pool

Improve  
Mechanical  
Properties

## Refinement of $\alpha$ -Al

Besides degassing, the development of cavitation promotes significant undercooling and formation of numerous solidification nuclei.

## Si and Intermetallics modification

Grain refinement exerts a positive influence on several properties of cast aluminum, namely: porosity, shrinkage distribution, intermetallics distribution and mechanical properties.

*Ultrasonic solidification*

# What is the role of casting / foundrymen in improving the properties of aluminum alloys?

- Control of melting process.
- Melt treatment: degassing, microstructure refinement and modification.
- Assessment of variables which could contribute to improved castings.

**and...**

# Application of acoustic waves in treating of melt aluminum alloys.

*A promising future*



Ultrasound above the threshold of acoustic cavitation can be introduced into a molten metal (e.g. during the continuous casting process), this way promoting:

Degassing of liquid metals using high intensity ultrasonic activity.

Ultrasonic grain modification technology (improving micro crystallization).

Ultrasonic filtering and refining of molten metal.

Ultrasonic mixing and homogenizing of liquids is exceptionally efficient.

Liquids and liquid metals that do not mix in normal conditions can also be mixed in number of combinations, homogenized and/or alloyed in high intensity ultrasonic reactors, or in certain ultrasonically optimized casting process.

# Reality & Practice



How can I control the process...

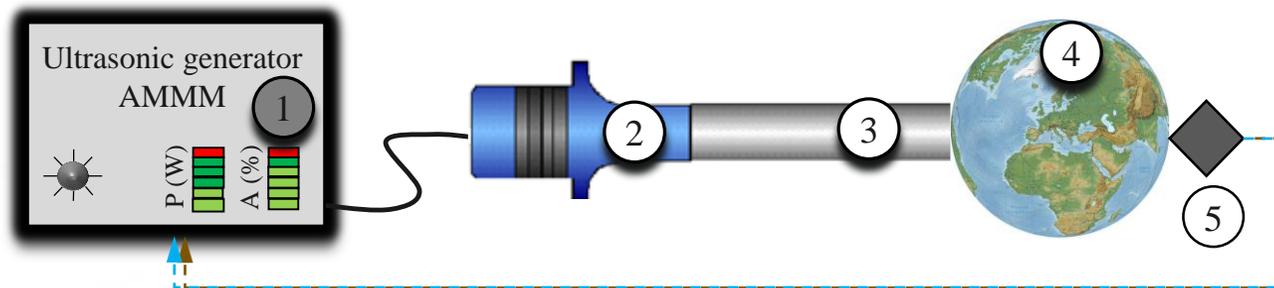
*Using the MMM Technology*

Can I control the process with my equipment...

*Yes, using MMM Technology (cavitation control)*

What are the best characteristics of "Ultrasonic Activity" ...

*Depends, but using MMM Technology you can chose*



1 High frequency Ultrasonic generator      2 Ultrasonic Transducer

3 Waveguide      4 Load (medium...)      5 Sensor

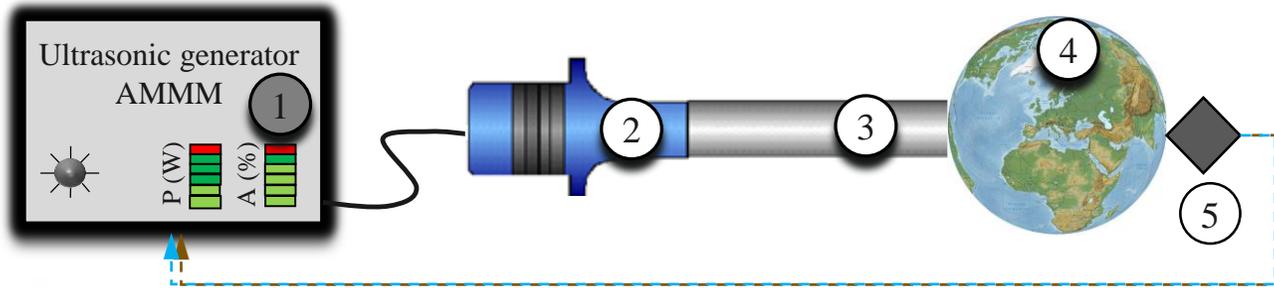
MMM Technology was developed by MPIinterconsulting.

Based in Switzerland MPI has clients around the world.

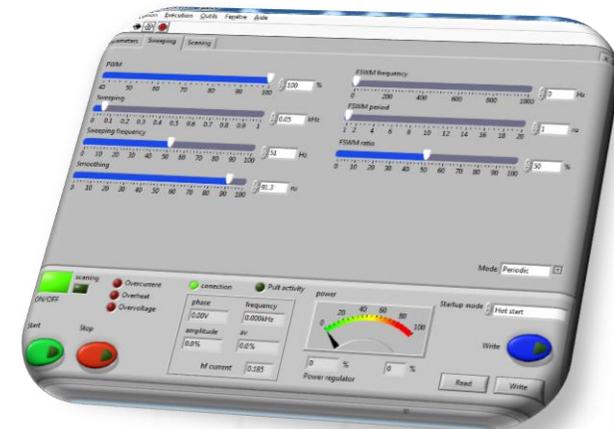
MPI offers products, R&D services and consultancy in high power Ultrasonics, a range of top quality ultrasonic [cleaning](#) and [sonochemistry](#) equipment and special equipment development for [new applications](#)

# Reality & Practice – Control Options

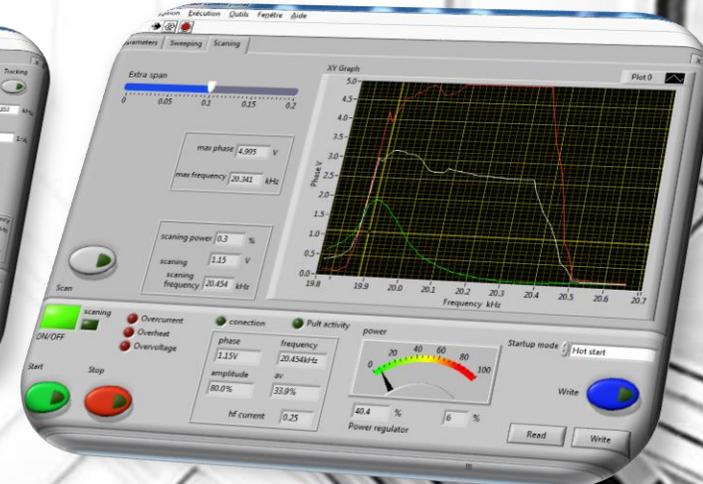
Based on specific Lab View, multi-windows monitoring software (where we can monitor several of significant parameters related to cavitation in a time and frequency domains).



- 1 High frequency Ultrasonic generator
- 2 Ultrasonic Transducer
- 3 Waveguide
- 4 Load (medium...)
- 5 Sensor

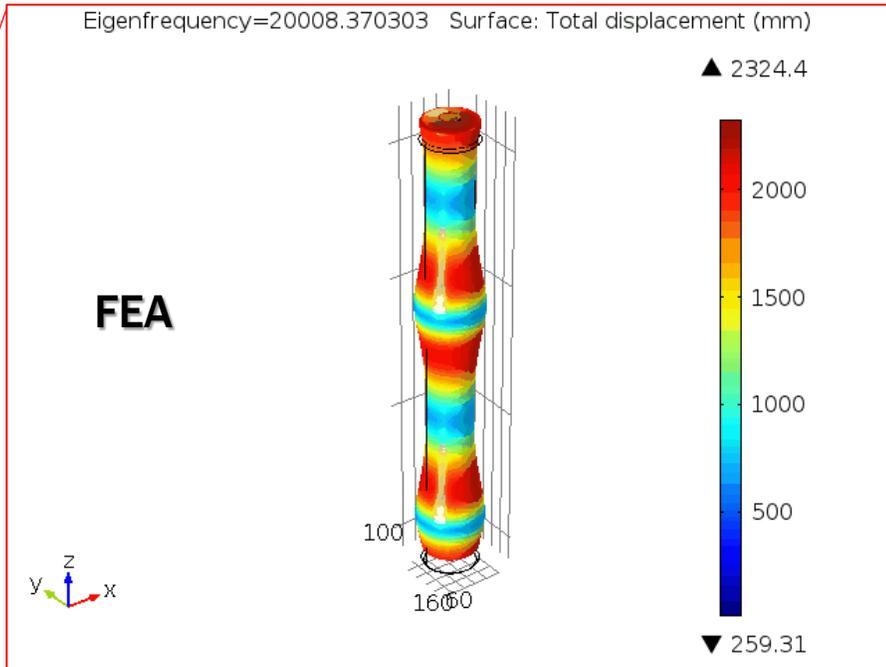
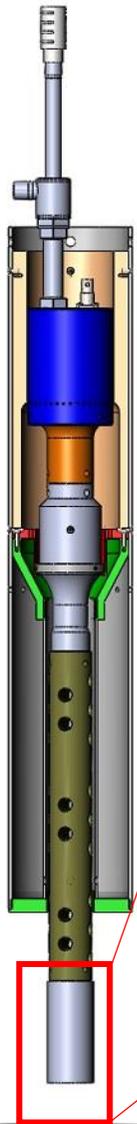


**Ultrasonic Generator Control Panel**





# Design options applied in processing of Light Alloy Melts

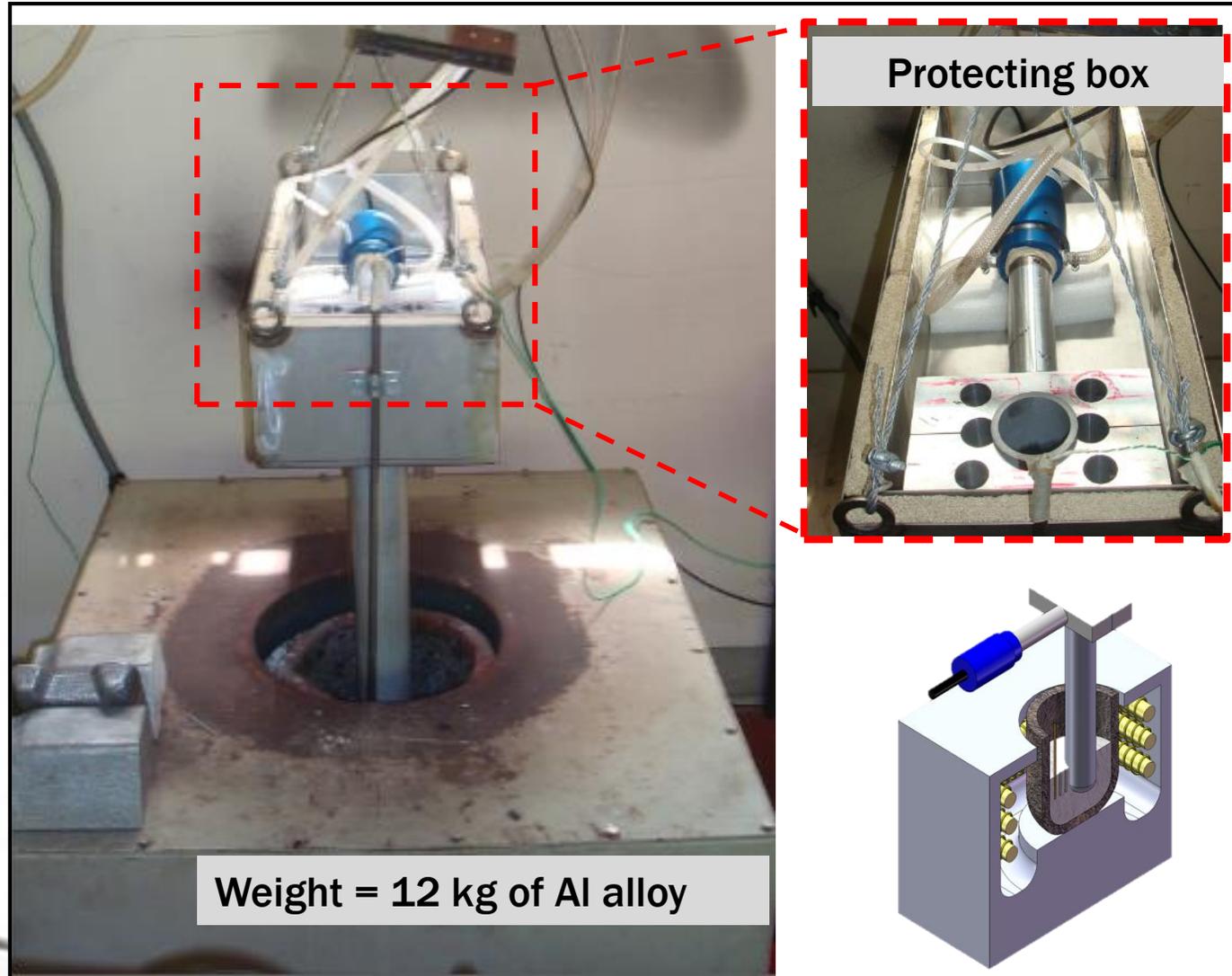


**Diameters from 35 to 60mm.  
Length from 1HWL to 4HWL.**



**Sonotrode material:  
Special Alloy resistant to wear with high  
amplitudes of vibration.**

# Different Design options applied in processing of Light Alloy Melts



Laboratory  
Foundry of  
University of  
Minho  
(Mechanical  
Department)

CT2M  
Center for Mechanical  
and Materials Technologies



# Different Design options applied in processing of Light Alloy Melts

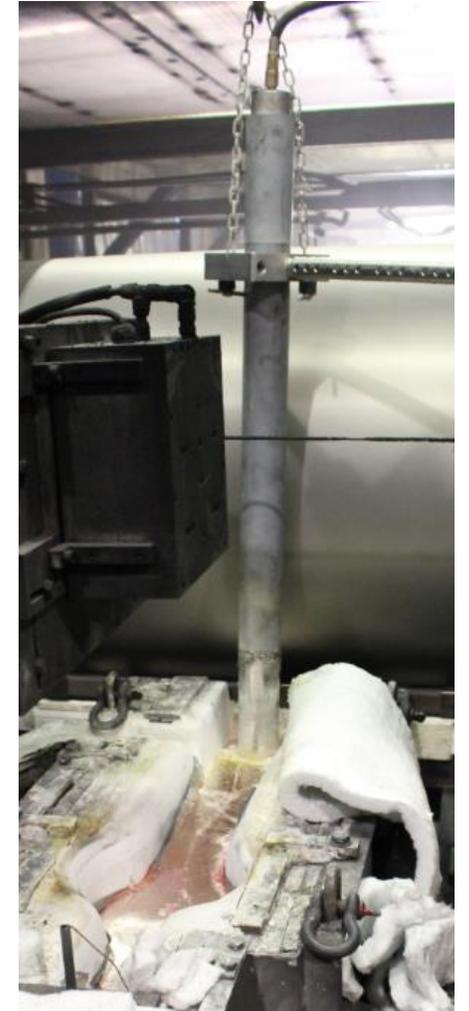
*in Industrial environment*



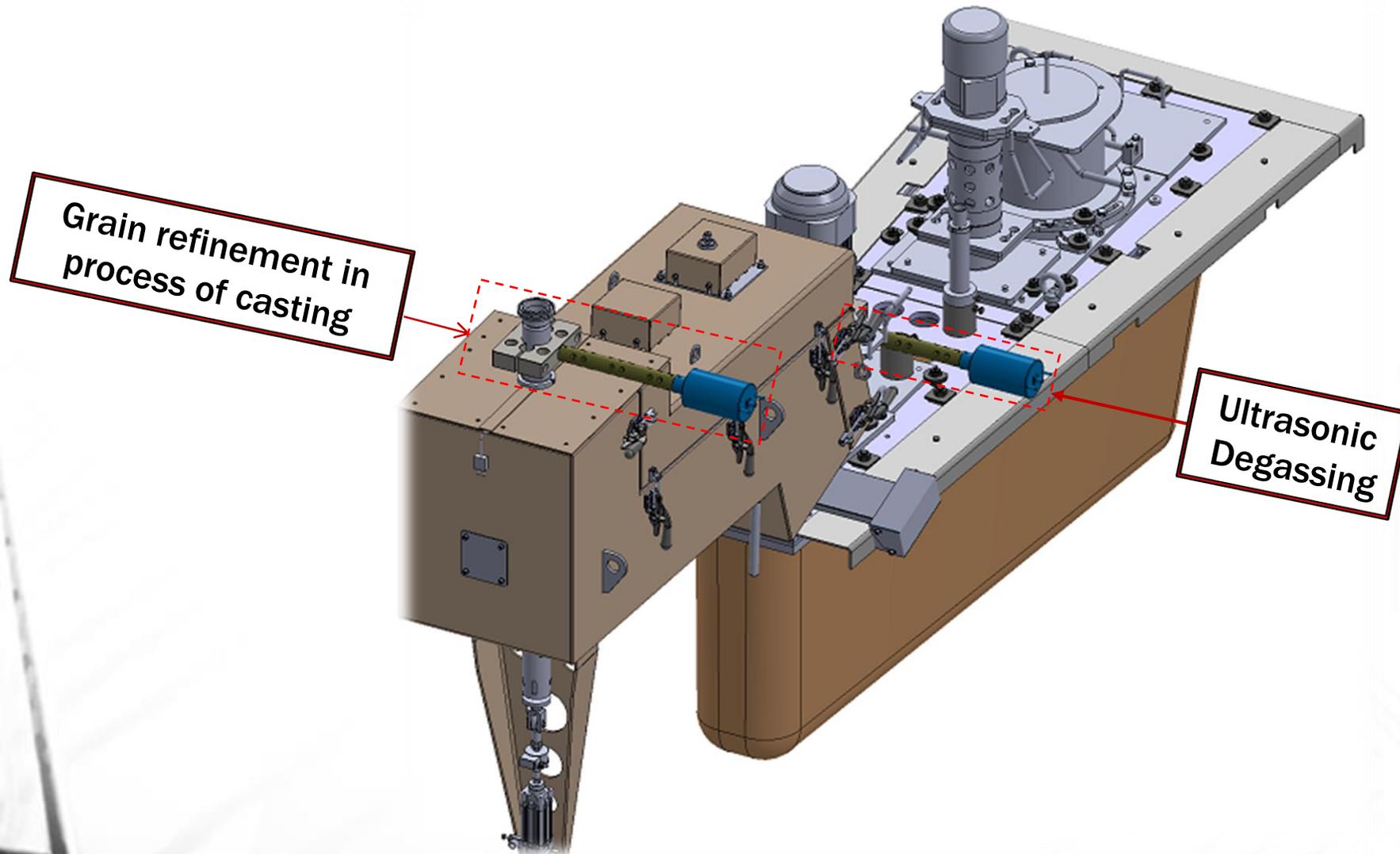
**Degassing  
treatment**



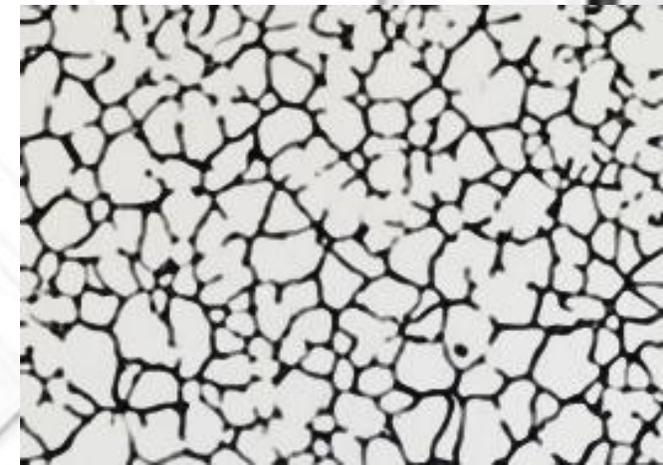
**Grain  
refinement**



# Design options applied in processing of Light Alloy Melts

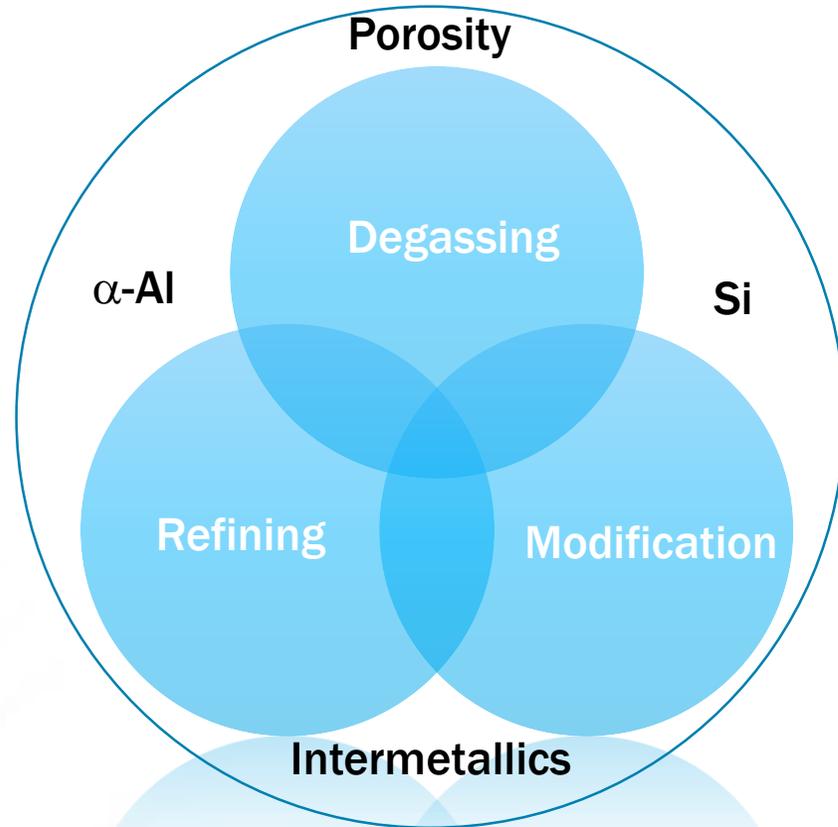


Light Alloys Furnace  
Ultrasonically optimized



*If we really understand the problem,  
the answer will come out of it,  
because the answer is not separate  
from the problem.*

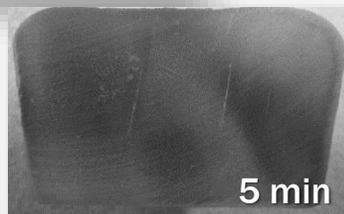
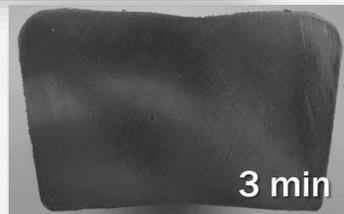
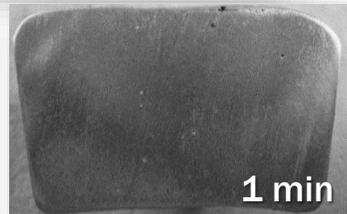
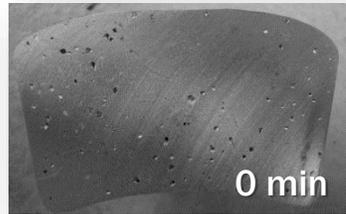
# Results of MMM technology in processing of Aluminum alloys



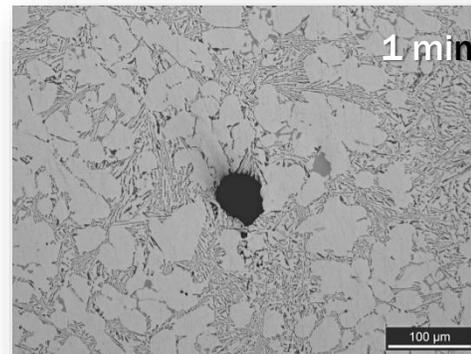
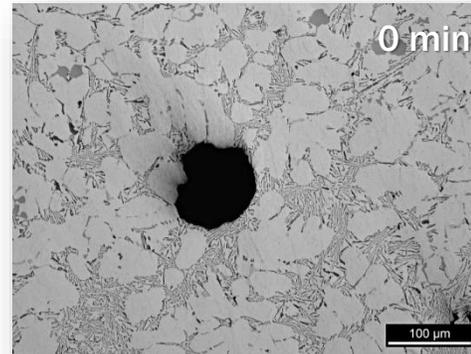
Results obtained with  
MMM Technology

# Static Casting, Ultrasonically Assisted

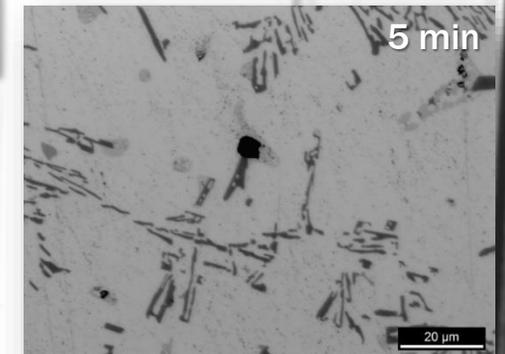
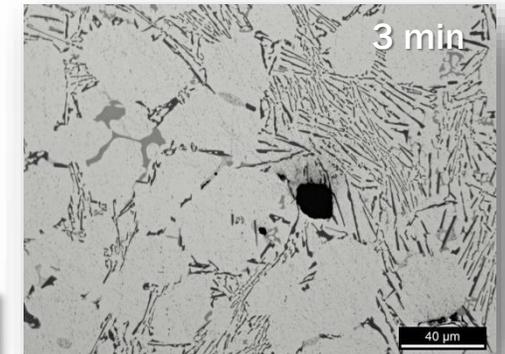
Some of our experimental results



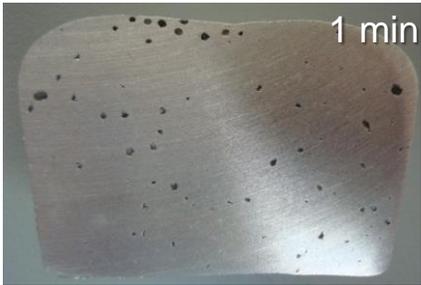
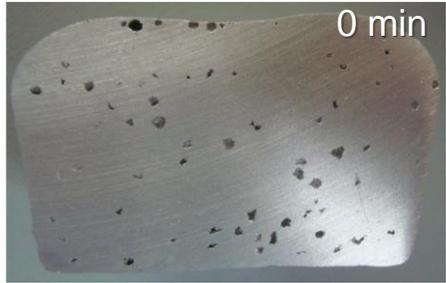
Samples  
RPT tests



Samples  
Porosity

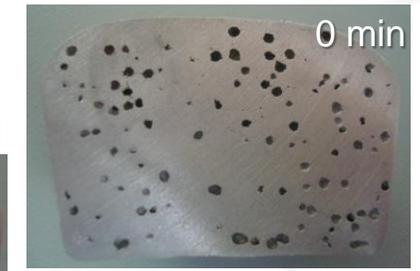
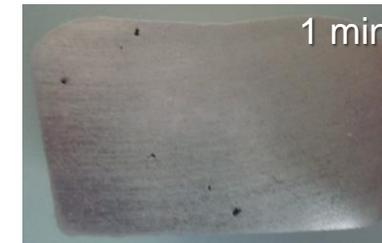
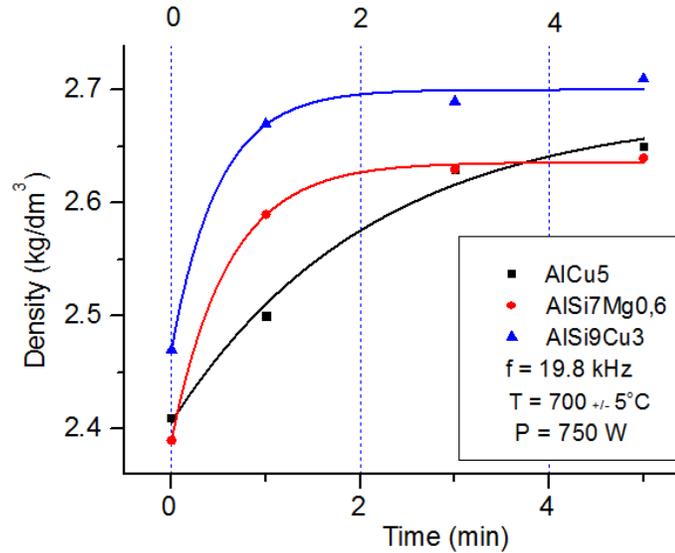


# Static Casting, Ultrasonically Assisted

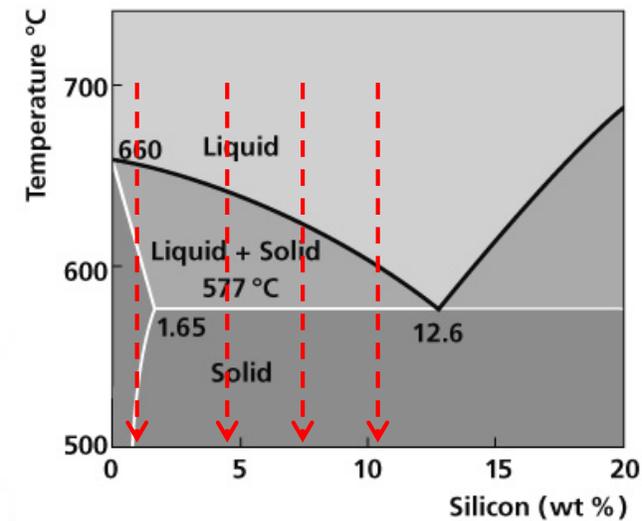
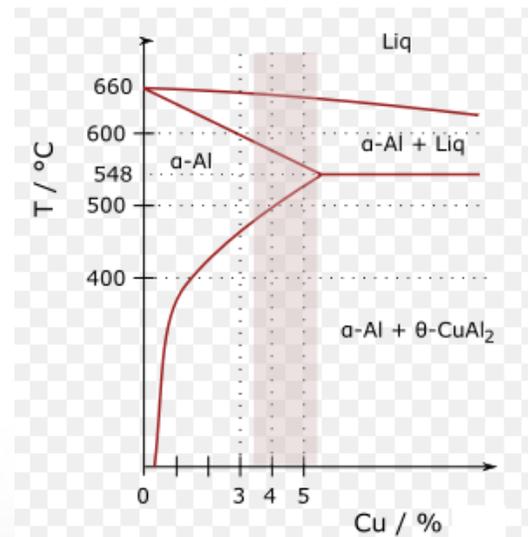


Al-Cu

## Some of our experimental results

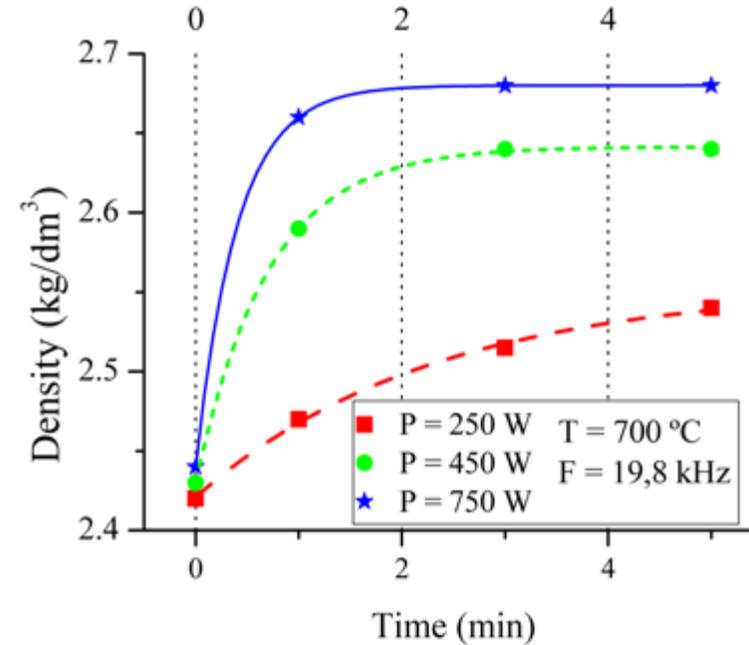
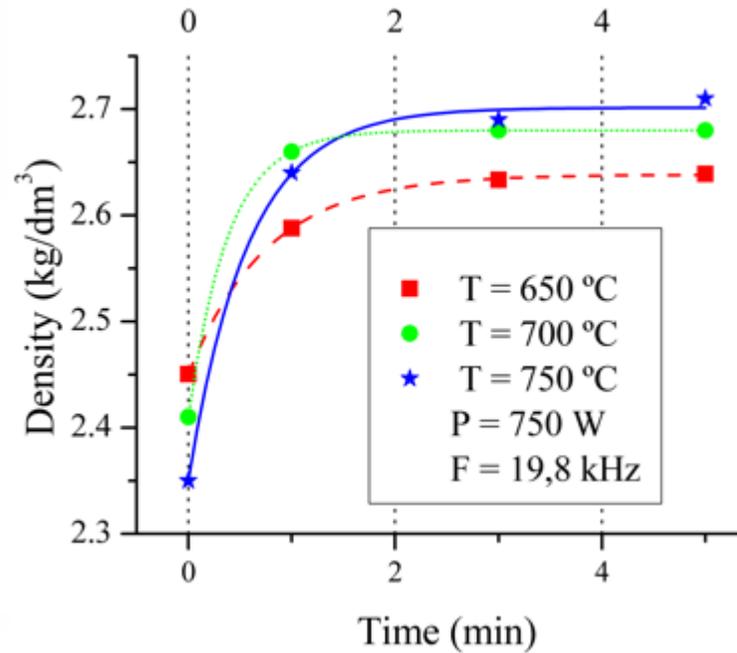


Al-Si-Mg



# Static Casting, Ultrasonically Assisted

Some of our experimental results



6.63 W/cm<sup>2</sup>

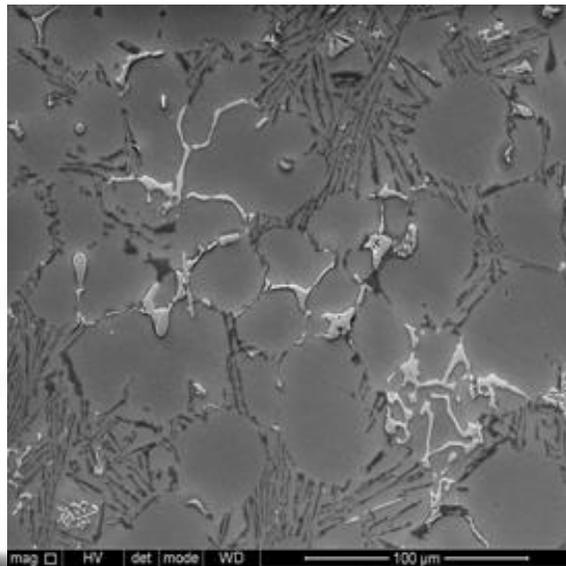
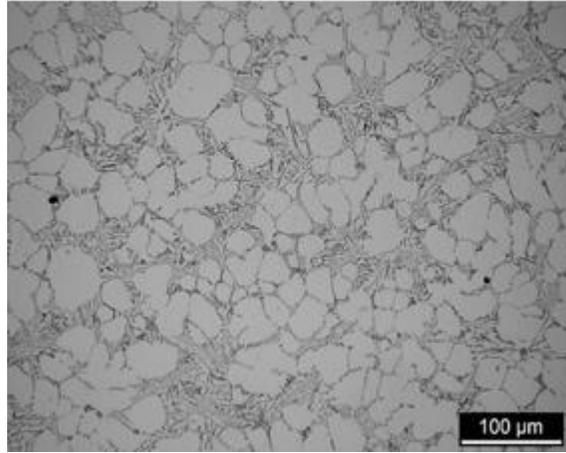
3.97 W/cm<sup>2</sup>

2.20 W/cm<sup>2</sup>

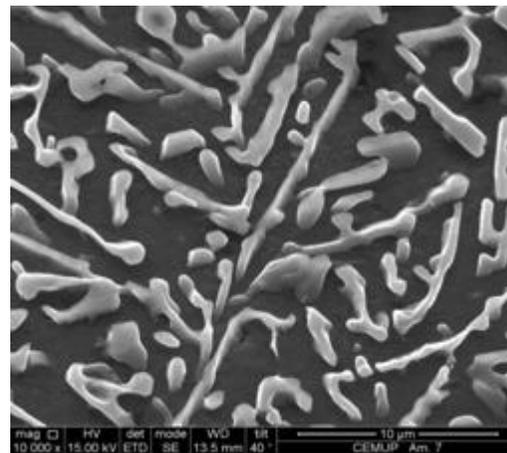
Effect of temperature and ultrasonic power in Al-Si-Cu processing

# Static Casting, Ultrasonically Assisted

Some of our experimental results



Al-Si-Cu after ultrasonic processing

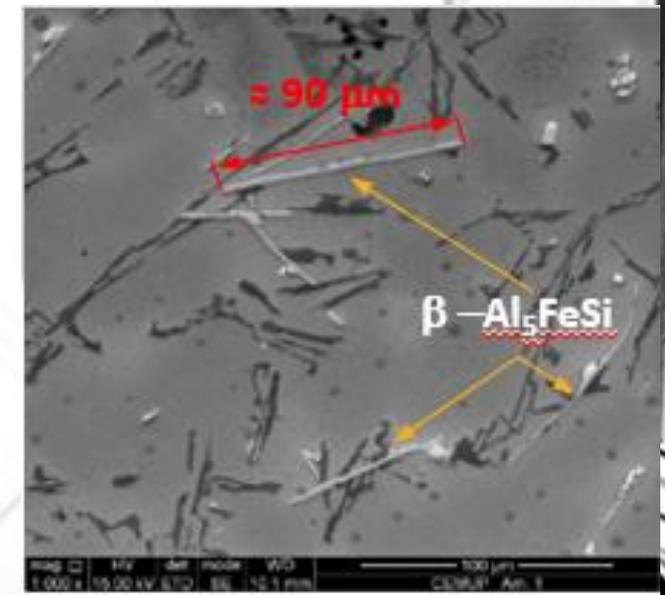
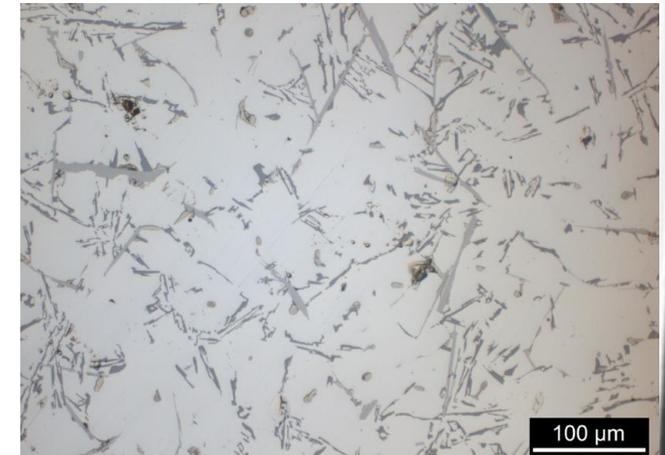


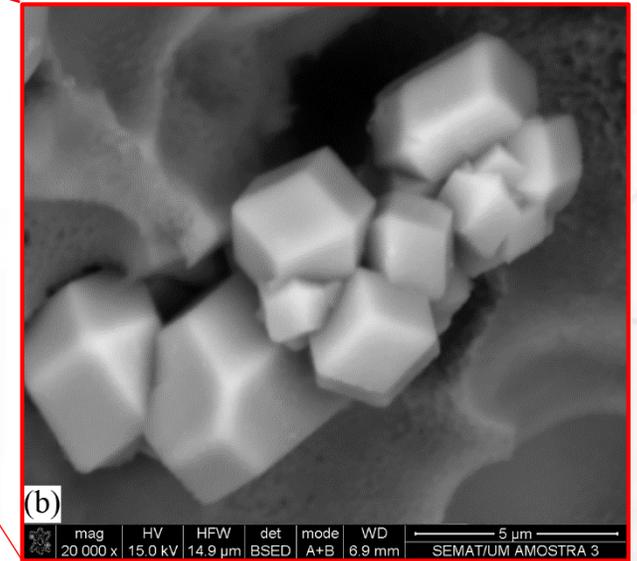
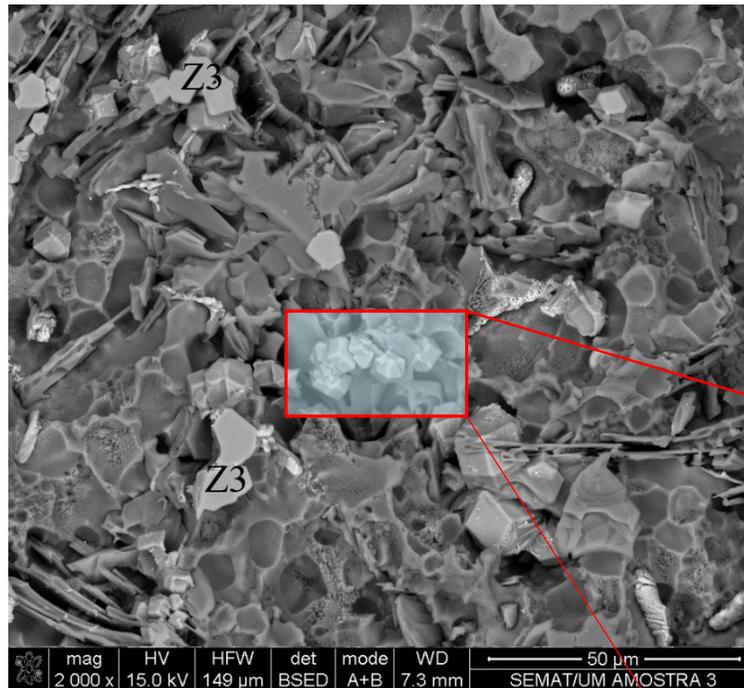
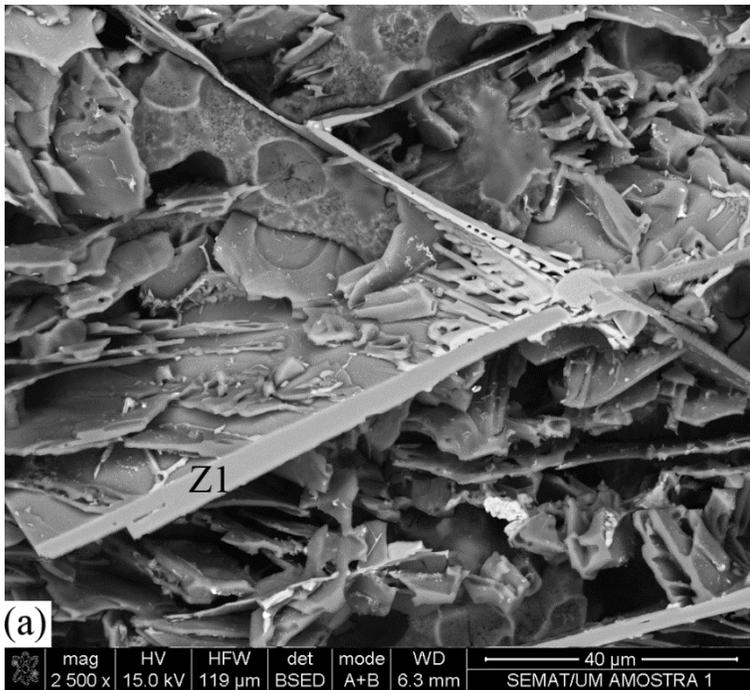
Samples

Refinement  
Modification

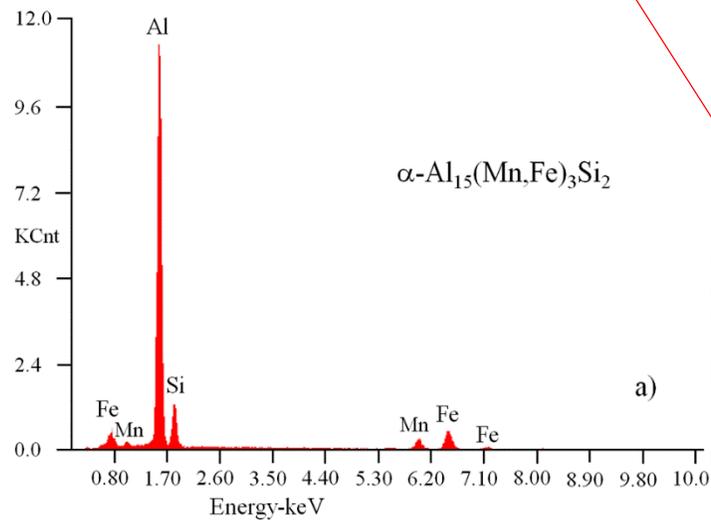
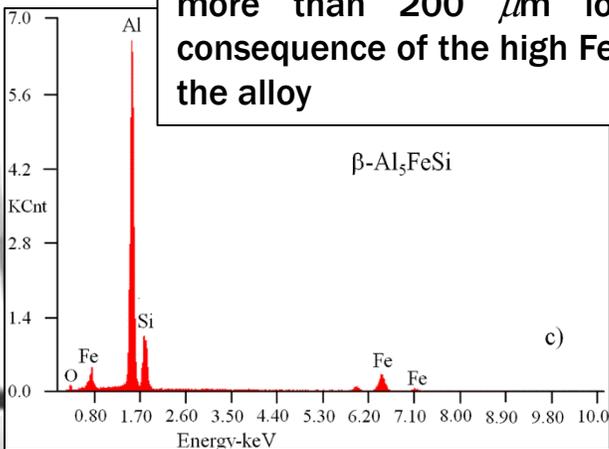
Optical microscope (OM) and Scanning Electron Microscope (SEM) with quantitative metallographic analysis capability were used to evaluate the shape and grain size of constituents

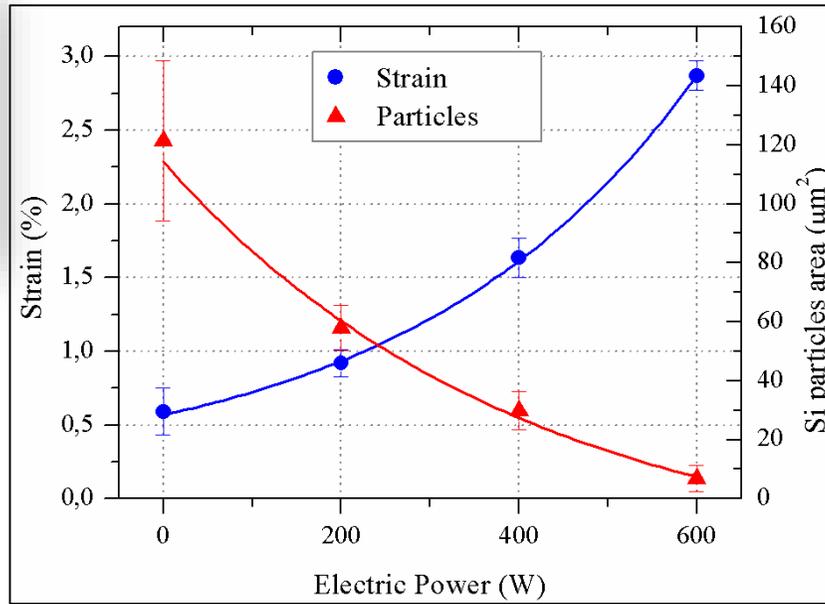
Al-Si-Cu before ultrasonic processing





The long needles of  $\beta\text{-Al}_5\text{FeSi}$  (light grey needles uniformly distributed in Figure 5 (b)) were, in some cases, more than  $200\ \mu\text{m}$  long, as a consequence of the high Fe content in the alloy





According to the microstructures shown in Fig.1, it appears that the supply of acoustic energy to the melt during the stage of solidification has a high potential to change the morphology of eutectic silicon. In fact, the silicon lamellar/acicular morphology, typical for unmodified alloys (Fig.2) was transformed into a fibrous structure with rounded edges, compact and shaped polygons (Fig.3), of ultrasonically modified alloys.

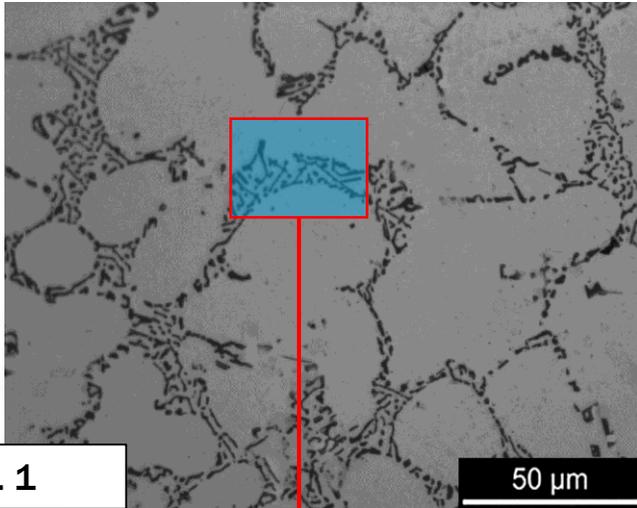
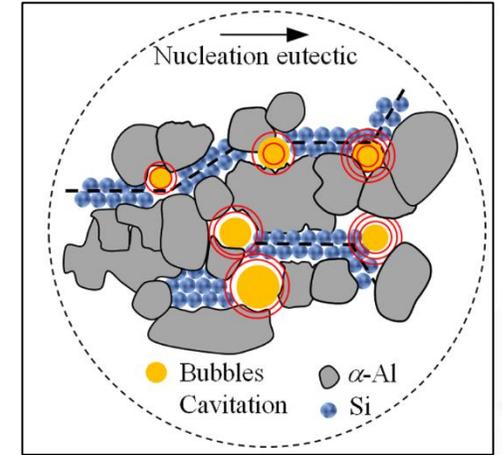


Fig. 1

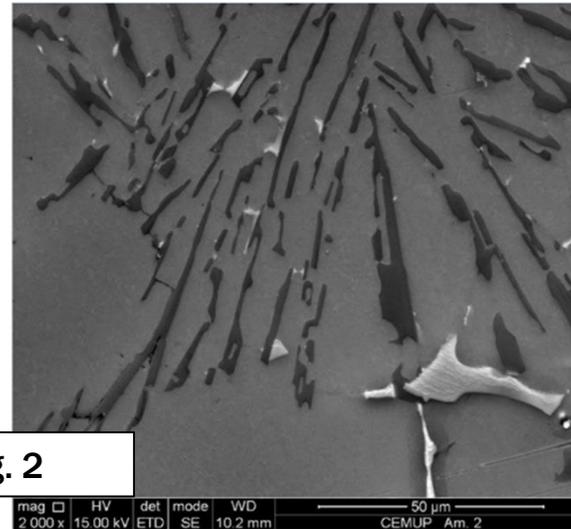


Fig. 2

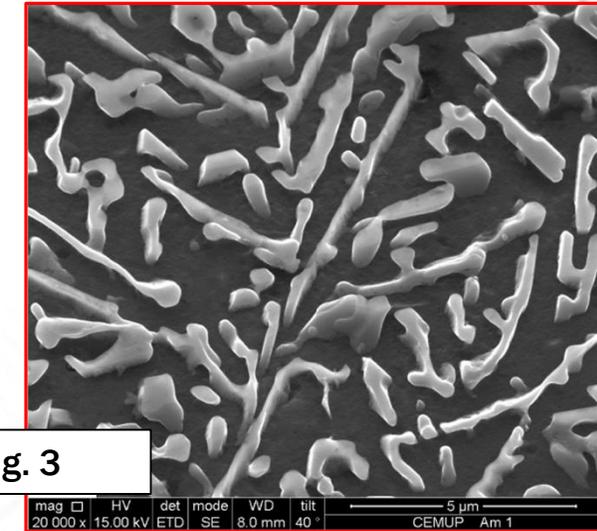
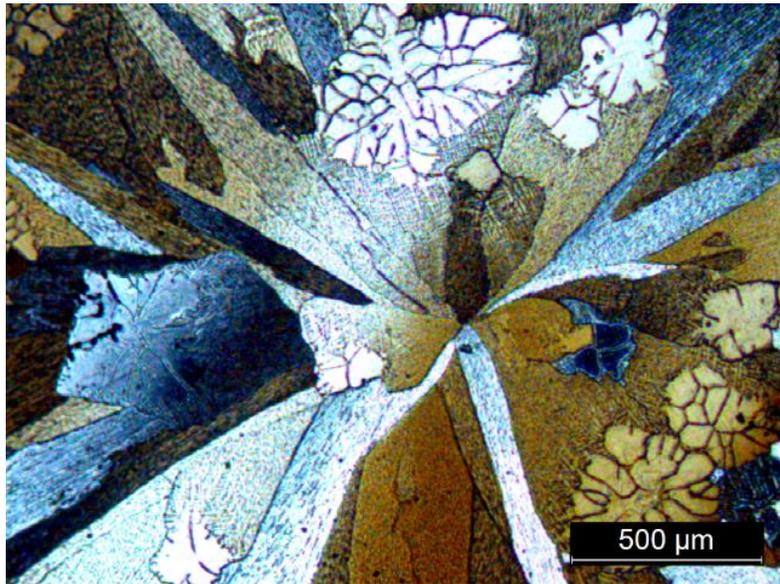


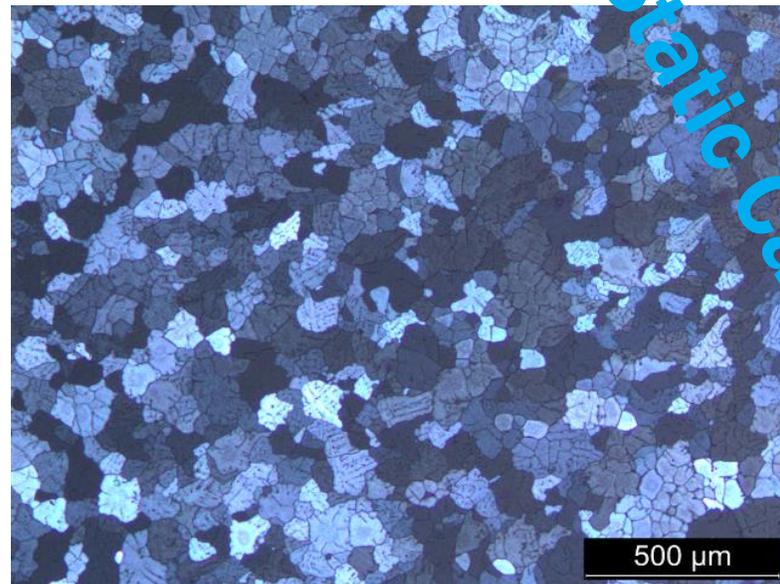
Fig. 3

# Static Casting, Ultrasonically Assisted

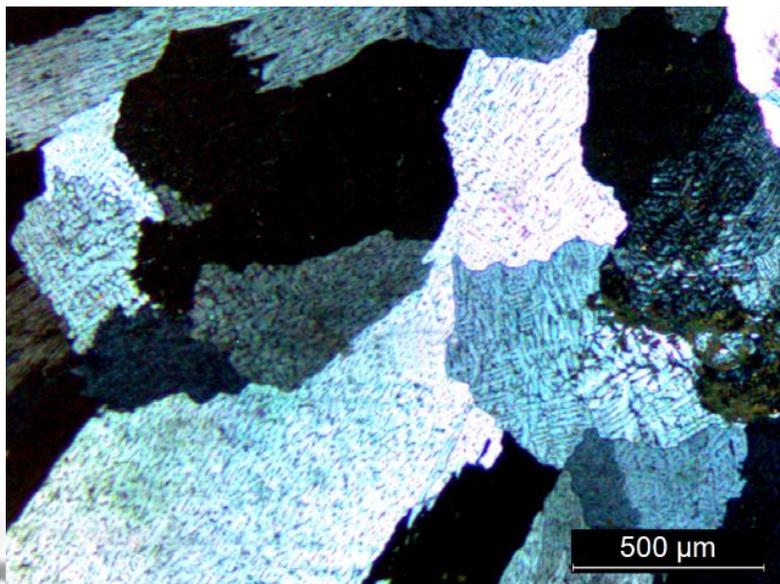
AlSc



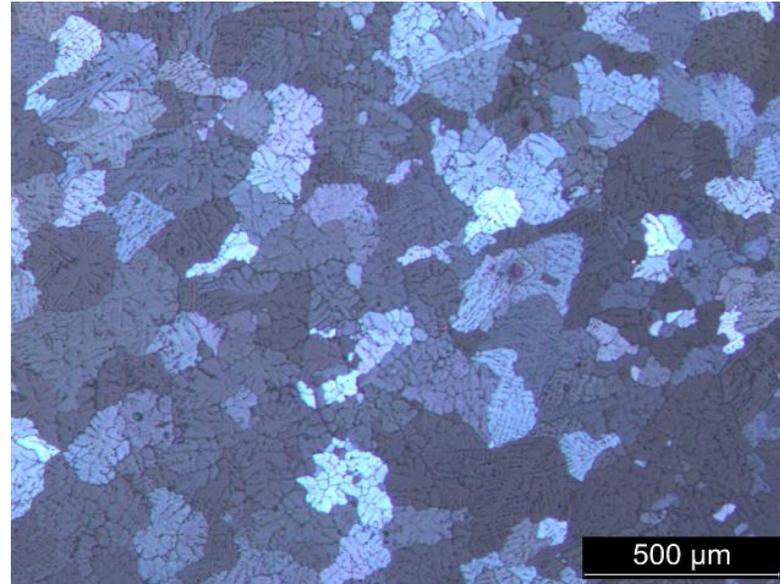
AlSc+US



AlScMg



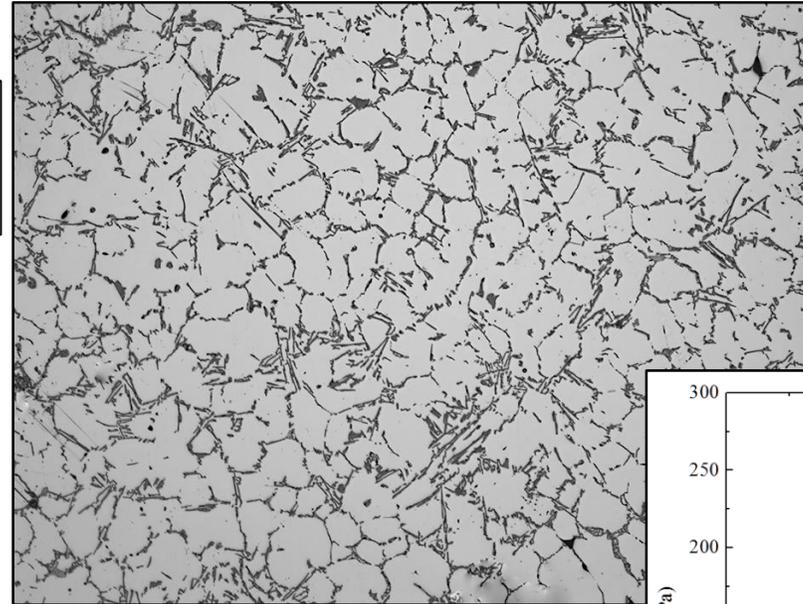
AlScMg+US



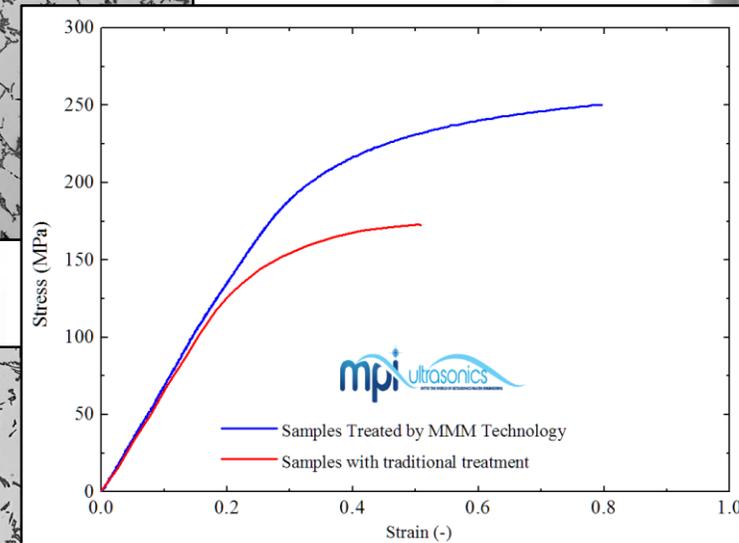
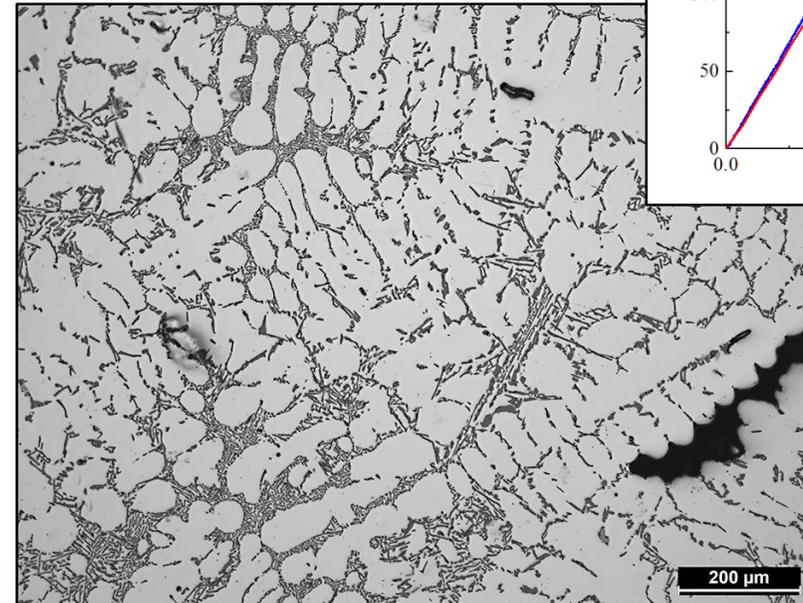
Static Casting, Ultrasonically Assisted

## Treatment With MMM Technology

Application of ultrasonic treatment during cooling of casting in sand mold.



## Tradicional Treatment



$T_{\text{casting}} = 700^{\circ}\text{C}$

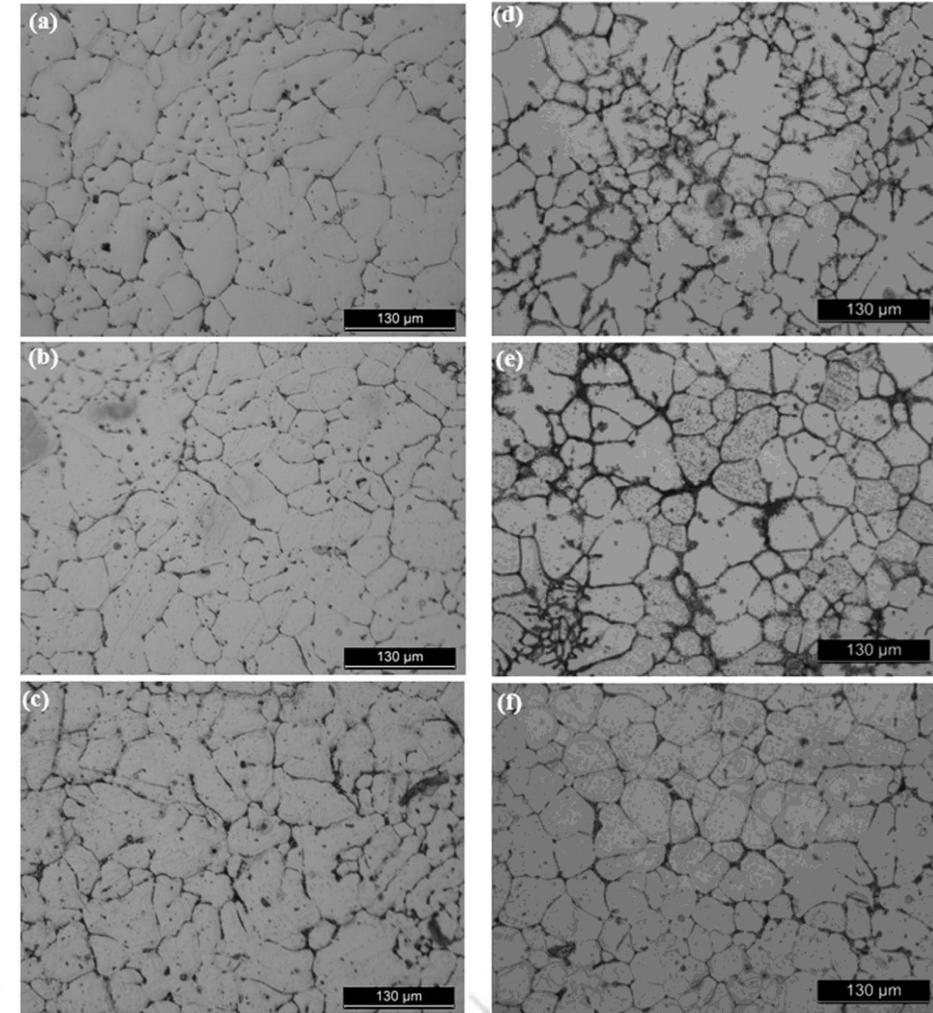
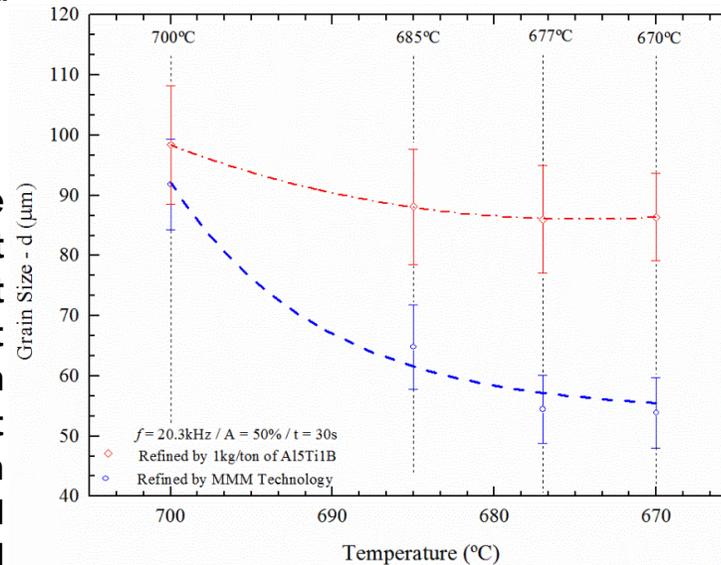
AlSi7Mg

# Continuous Casting, Ultrasonically Assisted

The efficiency of ultrasonic treatment (UST) depends on many factors, namely the ultrasonic parameters, such as amplitude and frequency of vibration, the degassing conditions (melt treatment temperature and processing time), the alloy composition, the material purity, and volume, all of great importance in the obtained results.

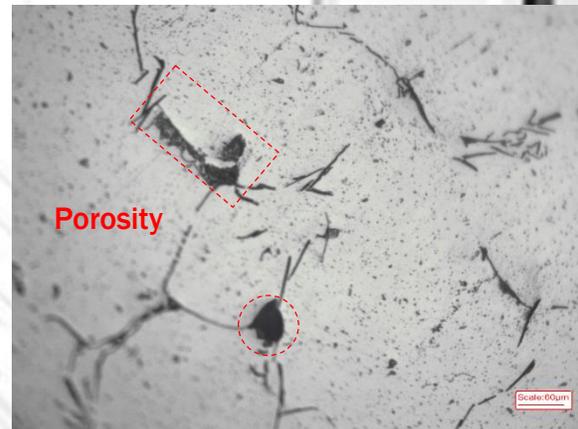
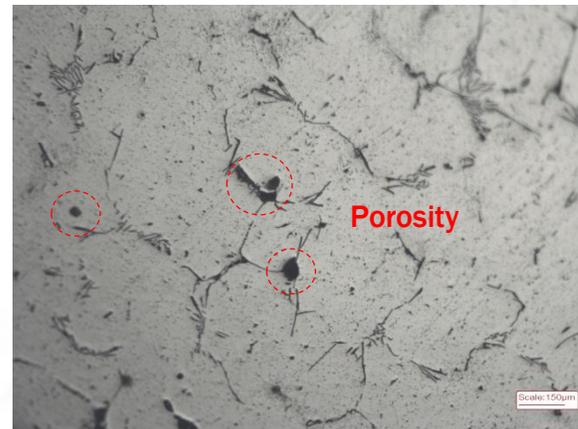
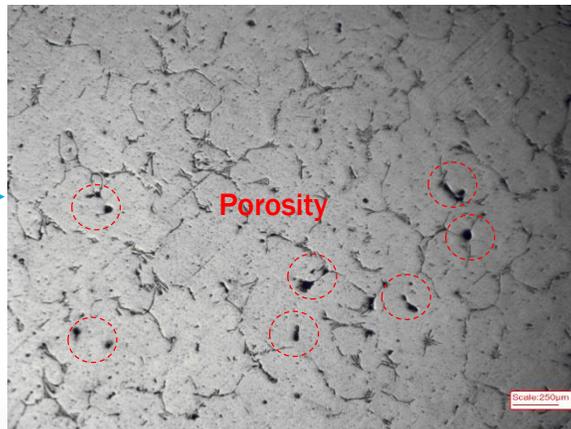
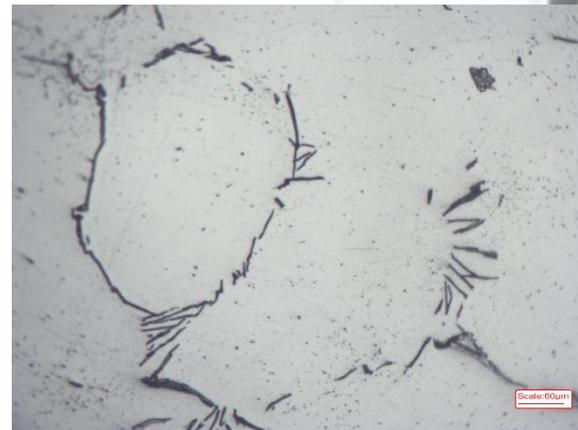
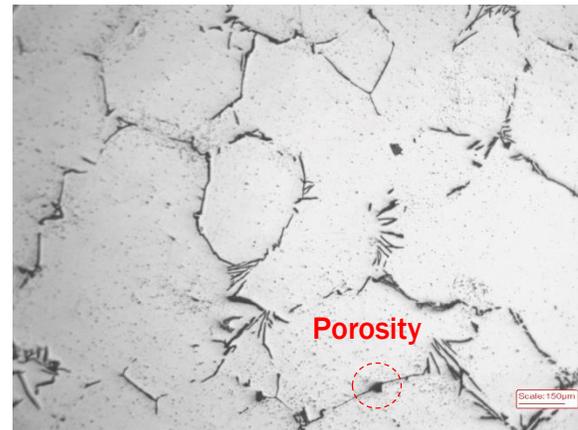
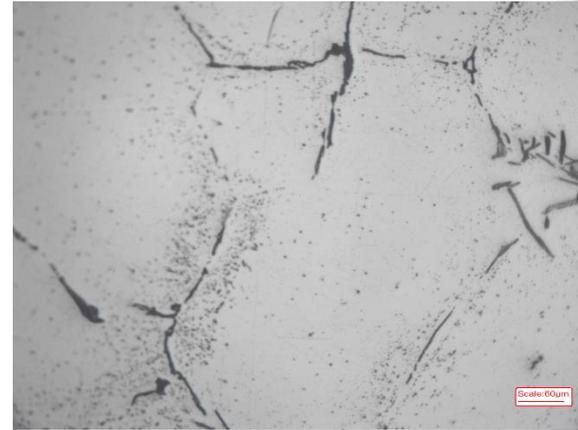
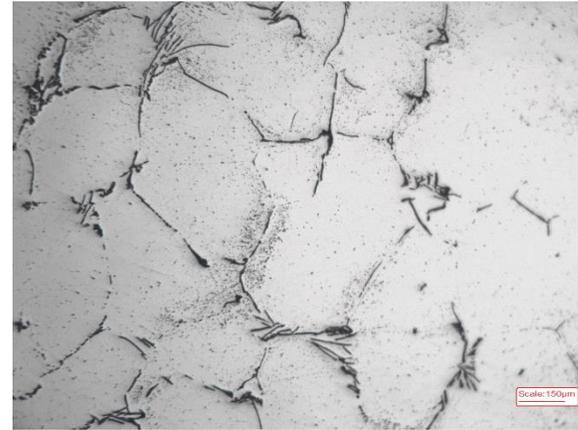
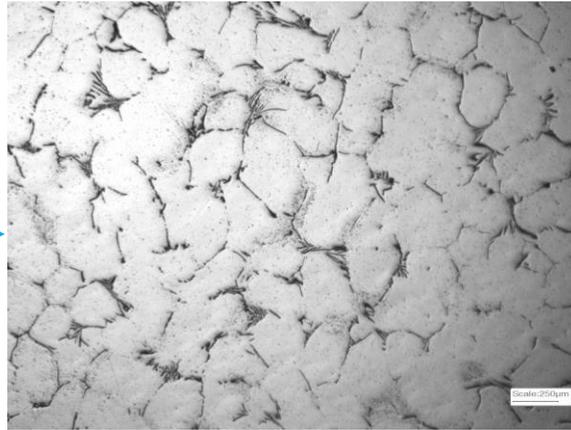
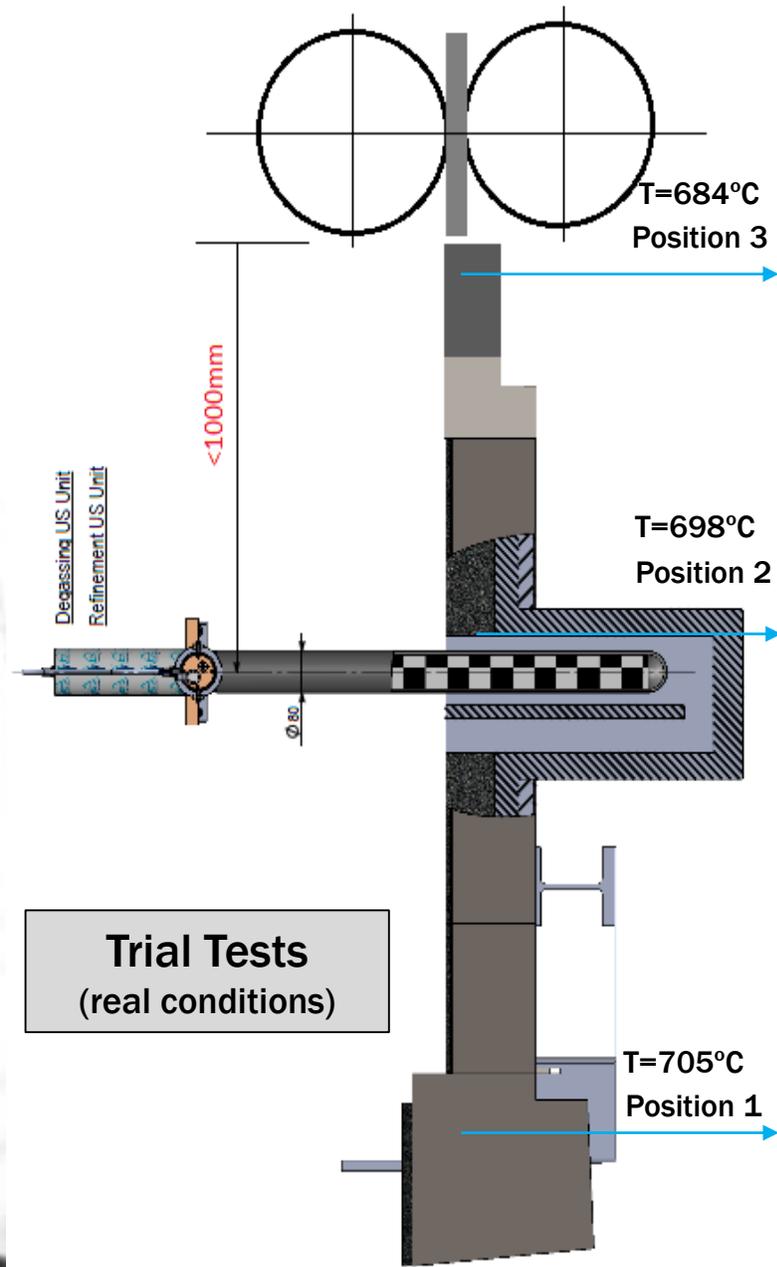
The Figure presents the as-cast microstructure of the Al-Mg-Mn alloy processed by different refinement techniques at different temperatures. From Figure it is clear that ultrasonic treatment had a significant effect on the microstructure morphology of the as-cast alloys and the final microstructure depends on the US treatment temperature, when compared with microstructure obtained after conventional treatment (refinement with 1kg/ton of Al5Ti1B).

## Laboratory tests



Effect of liquid temperature on the microstructure after casting Al-Mg-Mn: (a-c) with 1kg/ton of Al5Ti1B; (d-f) with MMM Ultrasonic Technology. (a) and (d) casting at 700°C; (b) and (e) casting at 685°C; (c) and (f) casting at 670°C.

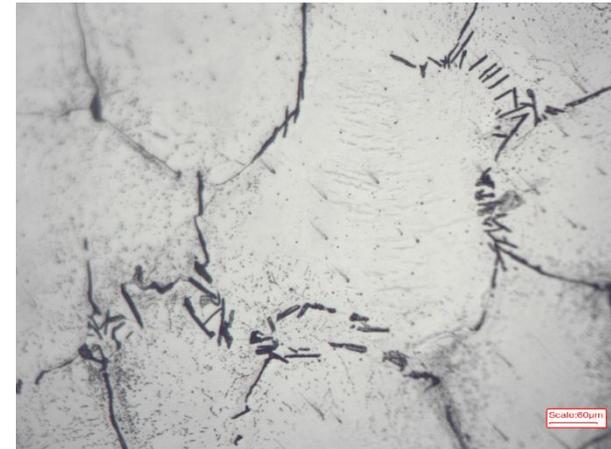
# A5xxx - Aluminum alloy from scrap





# DC Casting Simulation!

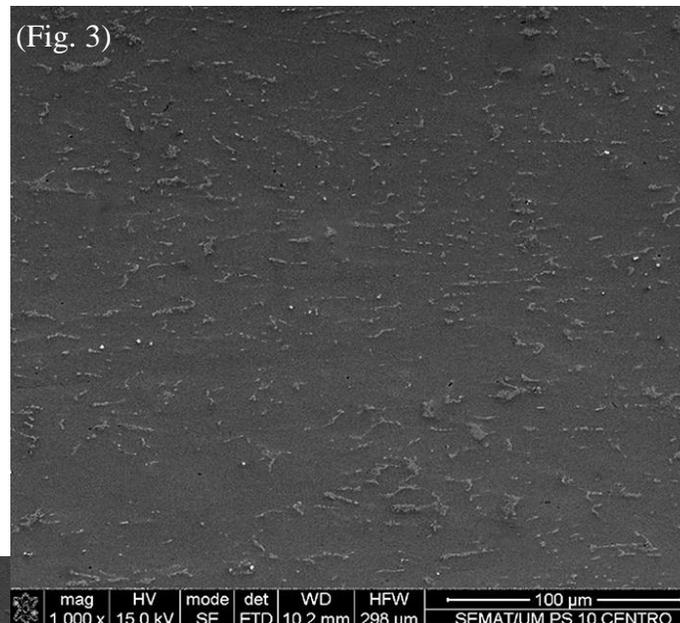
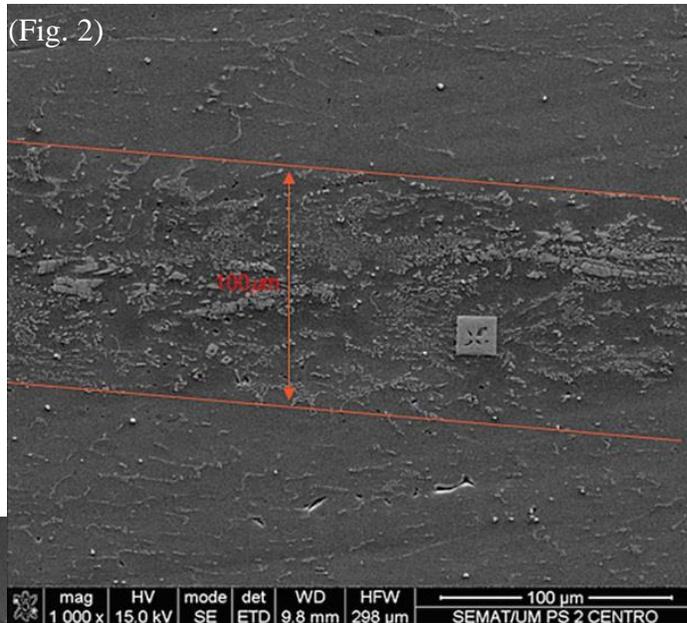
A5xxx - Aluminum alloy from scrap



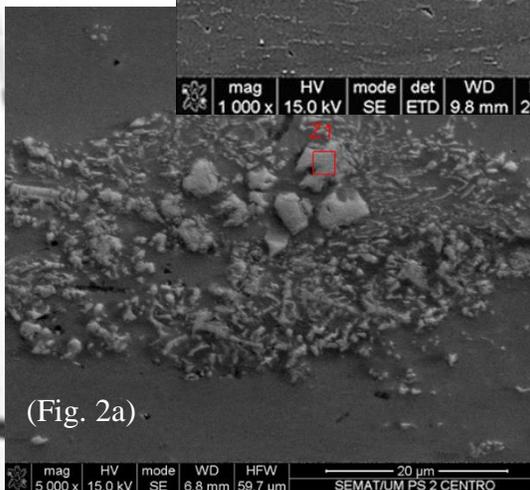
**Trial Tests**  
(real conditions)

# Continuous Casting, Ultrasonically Assisted

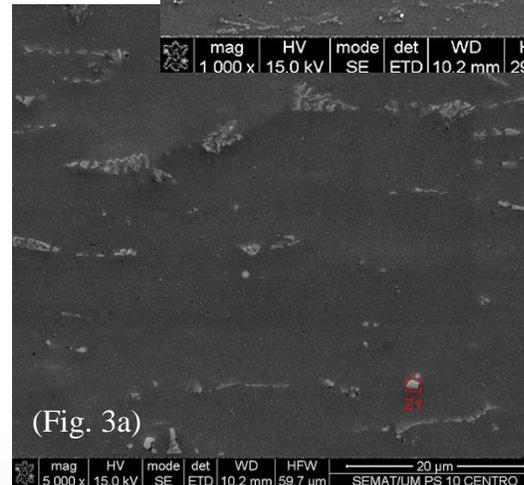
Trial was conducted on an industrial scale using the same alloy, according to the experimental results obtained in laboratorial scale. The Figure shows the contrasts of electronic microscopy microstructure of samples processed by traditional process (degassing by argon and refinement by addition of 1kg/ton of Al5Ti1B) (Fig. 1) and processed by MMM technology (regarding degassing and refinement) (Fig. 2). Fig. 1 shows the microstructure of the cross-section of alloy in which is clearly observed center zone segregation.



Besides the strong chemical segregation at the center of the strip (Fig. 2) and the crystals homogeneously distributed (Fig. 3), the SEM analysis revealed the co-existence of other intermetallic phases, as presented in Fig. 2a and 3a, which morphology, EDS X-ray spectra suggest presence of the composition of AlMnFeSi.



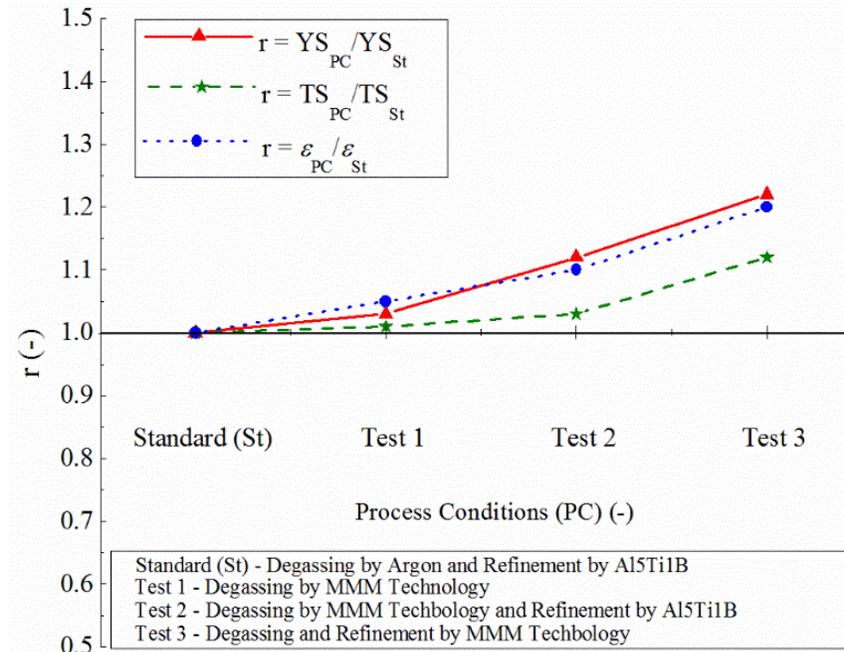
Microstructures of strips of Al-Mg-Zn alloy after twin-roll casting



When compared with the microstructure of the non-US processed samples (conventional process), the phases present in the US-treated samples (Fig. 3a) revealed a more uniform distribution, and their morphologies were significantly different.

# Continuous Casting, Ultrasonically Assisted

According to trial results is clear that is possible to increase alloy mechanical properties with a correct melt treatment, especially when ultrasonic treatment with MMM technology is applied (Test 3 – see Figure). These results are according to good homogenization of microstructure morphology and low level of porosity verified in the samples tested. Also, this results are according to bibliography where is mentioned that mechanical properties of Al alloys depend on several factors, namely to microstructure morphology and size and distribution of porosities.



Relation of mechanical properties of strips of Al-Mg-Zn alloy after twin-roll casting

In what concerns to microstructure refining and modification by ultrasound, the main conclusions to be drawn from the experimentation are:

- Ultrasonic degassing can be an efficient process to degas molten aluminum alloys.
- The degassing efficiency depends on the electric energy that is converted into acoustic energy, which affects the degassing rate and the final alloy density, but it is not affected by the resonant frequency;
- US processing is an external supply of energy – physical process – environmentally clean and efficient that promotes refinement of the  $\alpha$ -Al and eutectic Si phases, and decrease of porosity.
- US processing promotes the change of  $\alpha$ -Al dendritic morphology, which is typical in die-castings, into globular morphology, which size depends on applied ultrasonic power and the distance from ultrasonic radiation emitting surface.
- US processing promotes the amelioration of mechanical properties.
- Elimination of traditional argon degassing and replacement with ultrasonic degassing (savings in argon and electricity for mixing).
- Better alloying, wetting, disintegration, homogenization and integration of all metallic and non-metallic ingredients and impurities into a metal mass (we get: more homogenous, harder, no defect, no intermetallic long needle).

# Publications

## Physical modification of intermetallic phases in Al-Si-Cu alloys

J. Barbosa, H. Puga, J. Oliveira, A. S. Ribeiro, M. Prokic  
Materials Chemistry and Physics 148 (2014) 1163–1170

## Influence of indirect ultrasonic vibration on the microstructure and mechanical behavior of Al-Si-Cu alloy

H. Puga, J. Barbosa, S. Costa, A.M.P. Pinto, S. Ribeiro, M. Prokic  
Materials Science & Engineering A 560 (2013) 589–595

## Influence of ultrasonic melt treatment on microstructure and properties of AlSi9Cu3 alloy

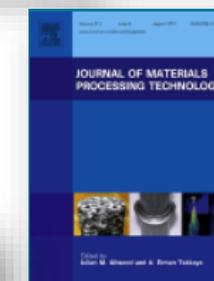
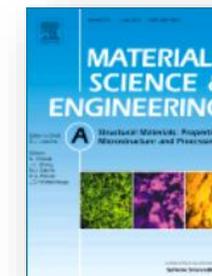
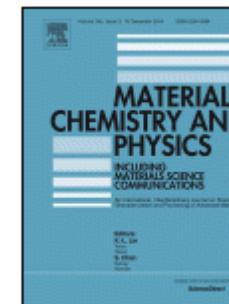
H. Puga, S. Costa, J. Barbosa, S. Ribeiro, M. Prokic  
Journal of Materials Processing Technology 211 (2011) 1729-1735

## The combined effect of melt stirring and ultrasonic agitation on the degassing efficiency of AlSi9Cu3 alloy

H. Puga, J. C. Teixeira, J. Barbosa, E. Seabra, S. Ribeiro, M. Prokic  
Materials Letters 63 (2009) 2089-2092

## The influence of processing parameters on the ultrasonic degassing of molten AlSi9Cu3 aluminium alloy

H. Puga, J. Barbosa, E. Seabra, S. Ribeiro, M. Prokic  
Materials Letters 63 (2009) 806-808



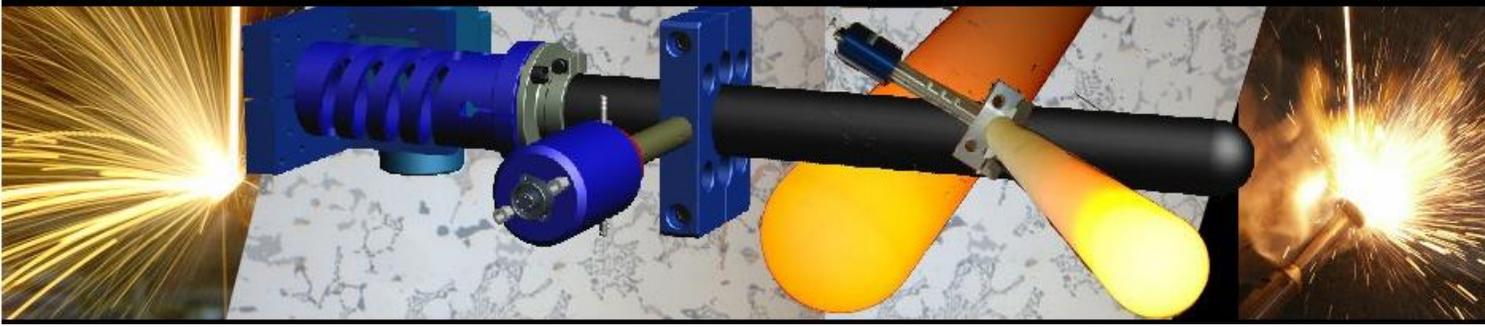
# Books

## Piezoelectric Transducers Modeling and Characterization

Miodrag Prokic, 240 pages, January 2004  
MPI, Le Locle, Switzerland,  
[www.mpi-ultrasonics.com](http://www.mpi-ultrasonics.com)

# Patents

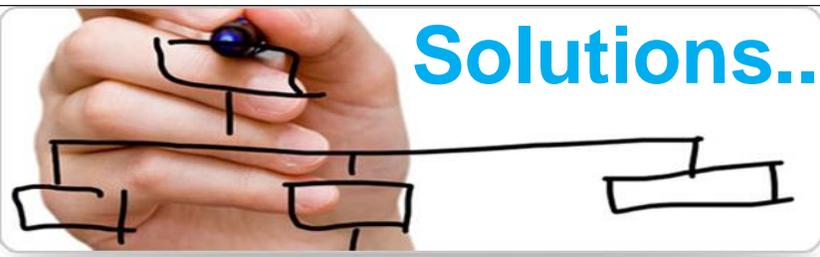
European Patent Application (related to MMM technology): EP 1 238 715 A1  
Multifrequency ultrasonic structural actuator  
Applicant: Prokic Miodrag, MP Interconsulting, 5.03.2001 – 11.09.2002



# Ultrasonic vibrations in metallurgy...

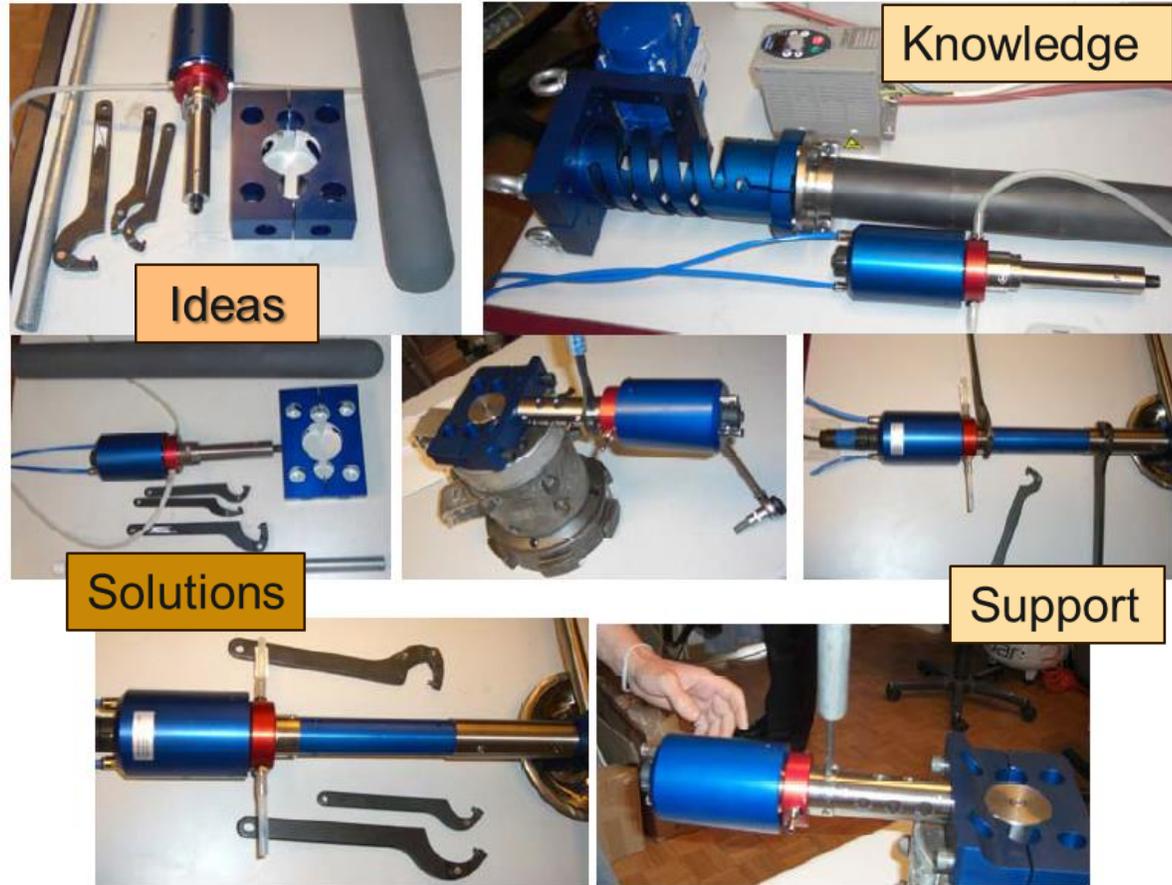
## Some ideas/proposal

**Part 2**



**What we need?**

- Improve the quality of products
- Save processing energy



**Thanks to MMM technology**

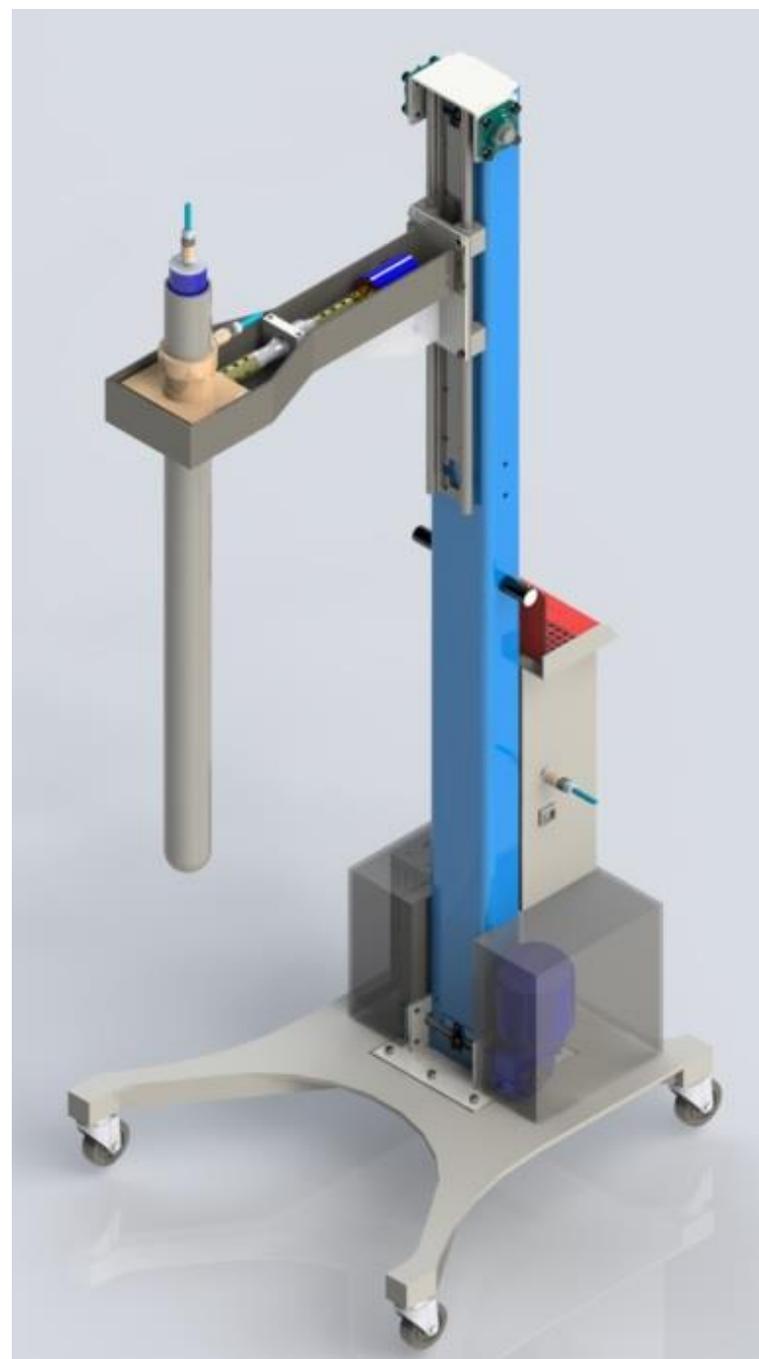
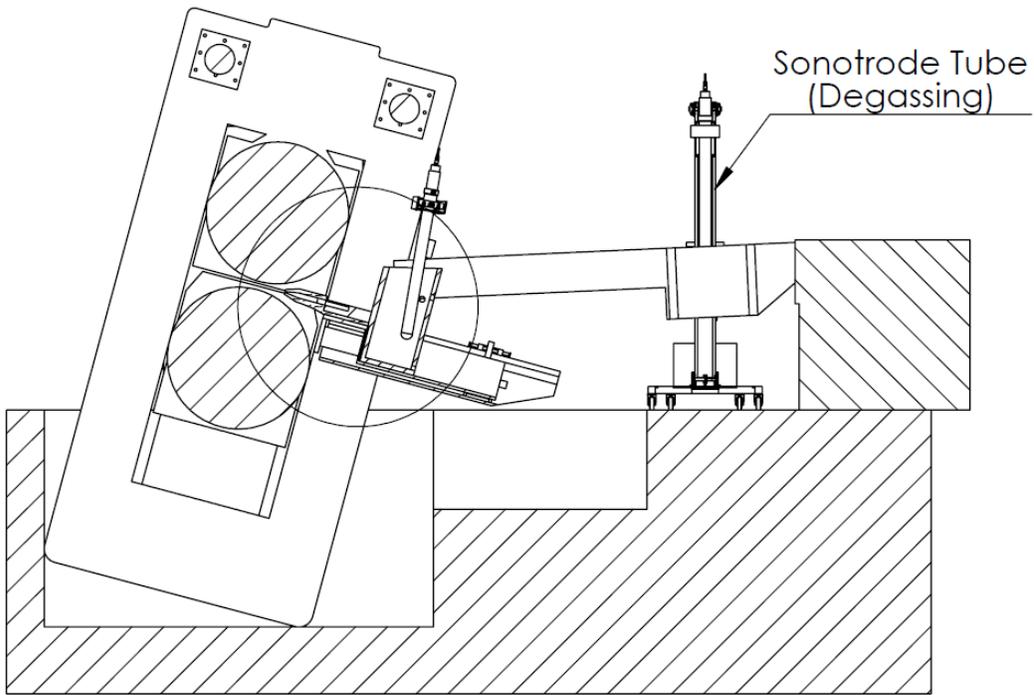
# Remarks

Traditionally available ultrasonic equipment for liquid metals treatment is still not compatible with high-volume, in-line metal processing (single frequency is creating standing waves and dead zones).

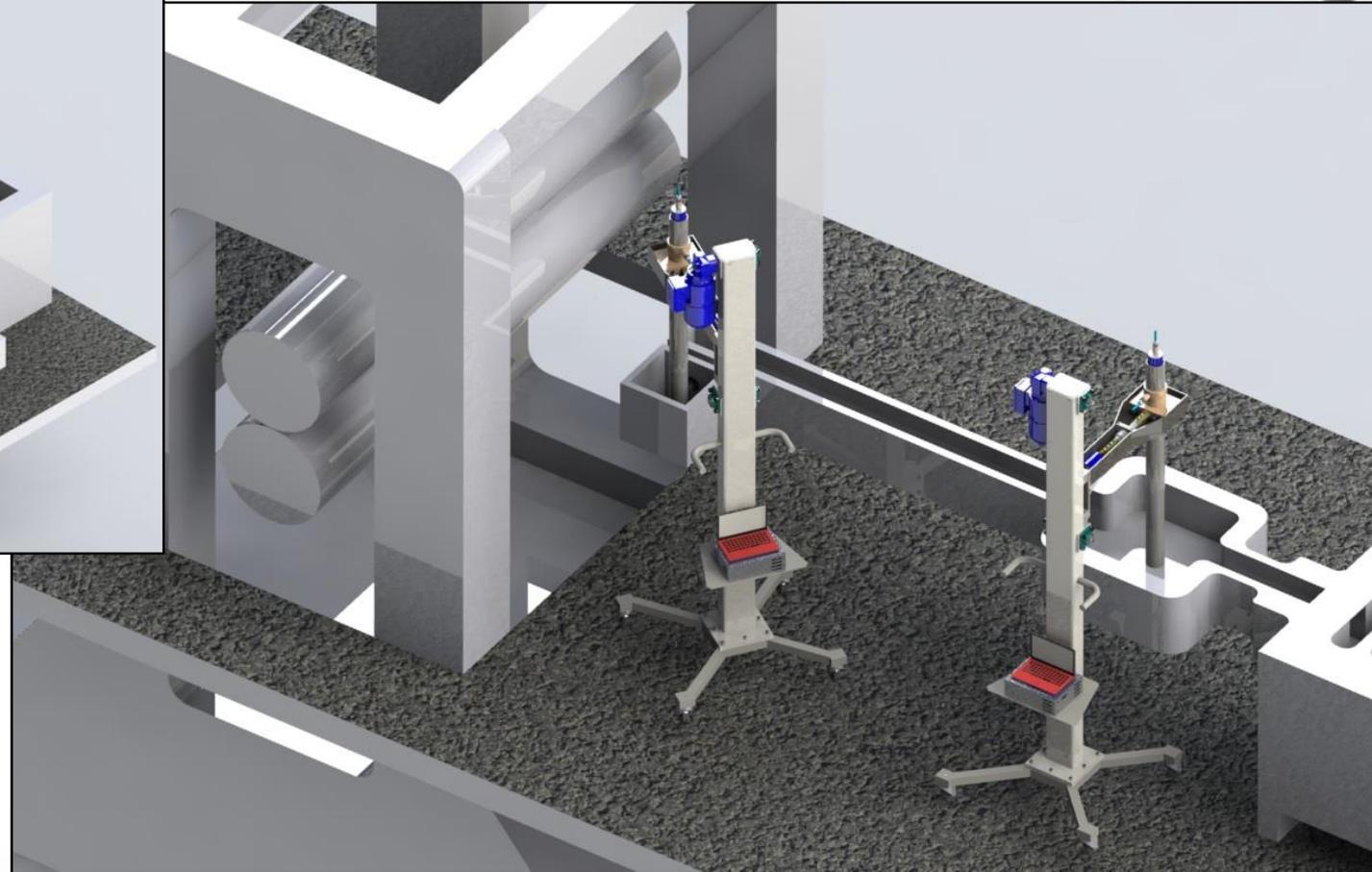
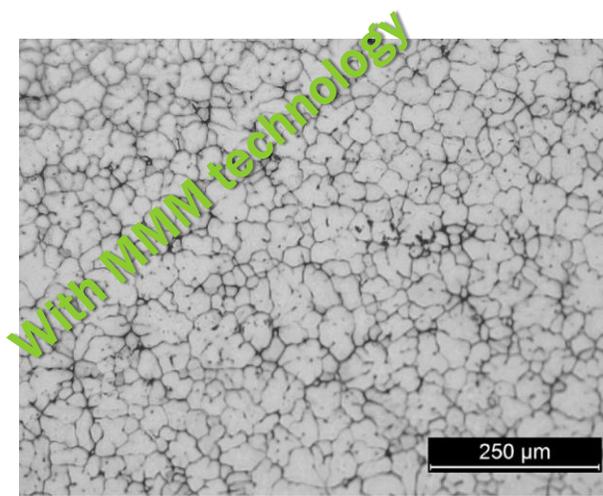
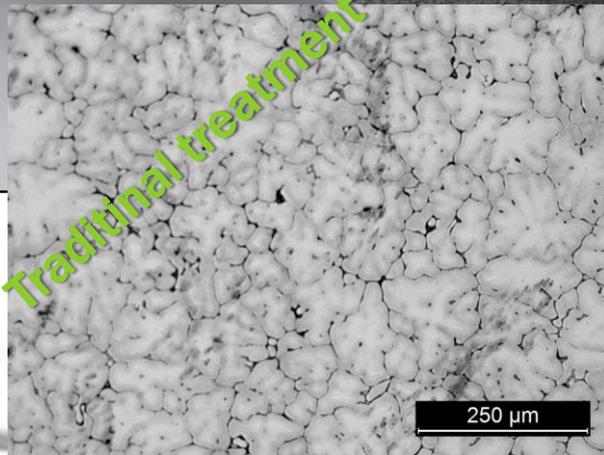
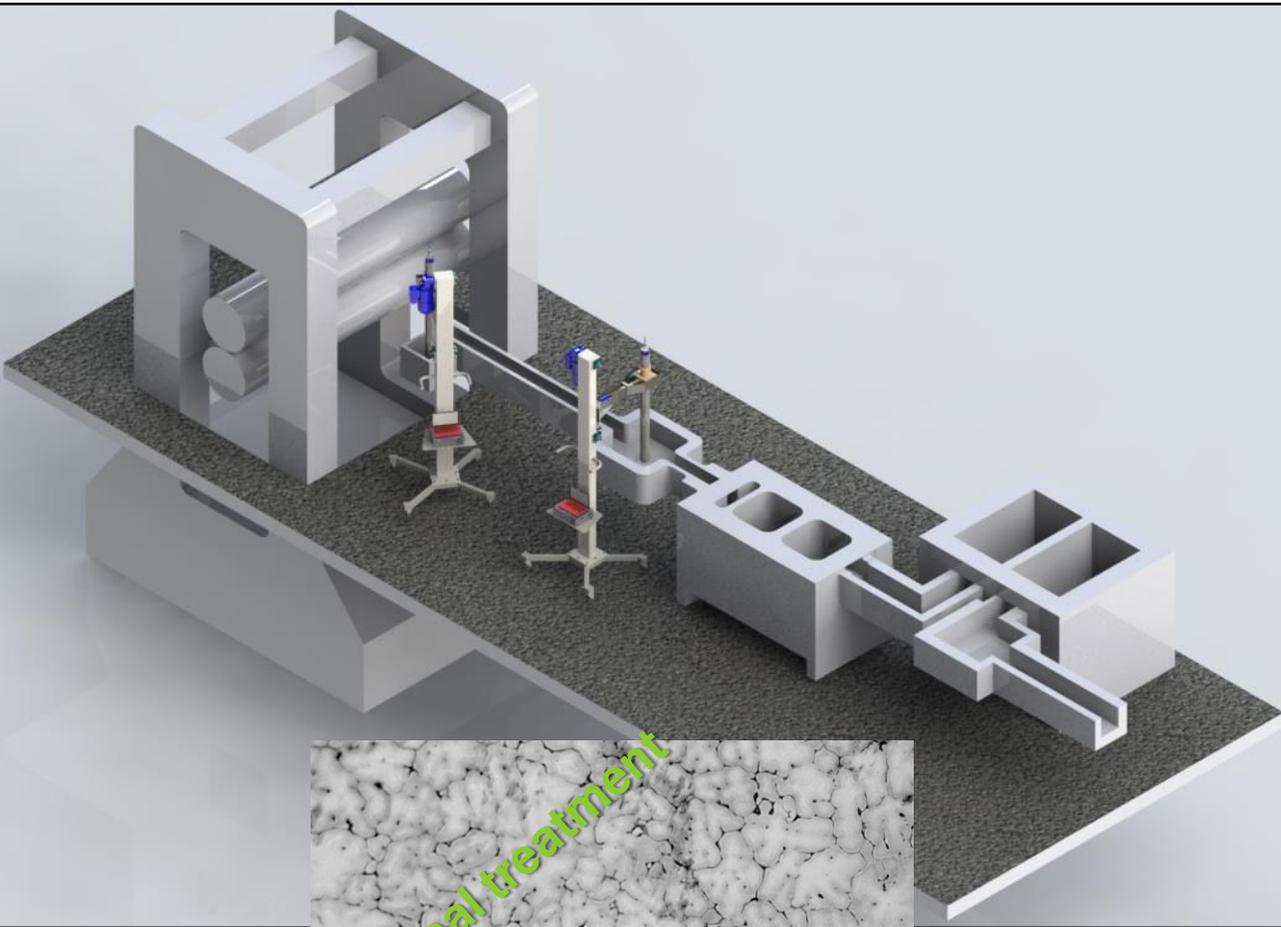
High temperature of liquid metals presents an enormous problem to continuous operation of ultrasonic transducers.

**We can now separate the ultrasonic transducers from the liquid metal using long metal waveguide rods, yet still introduce high ultrasonic power into liquid metals.**

## New Advances in Continuous casting process



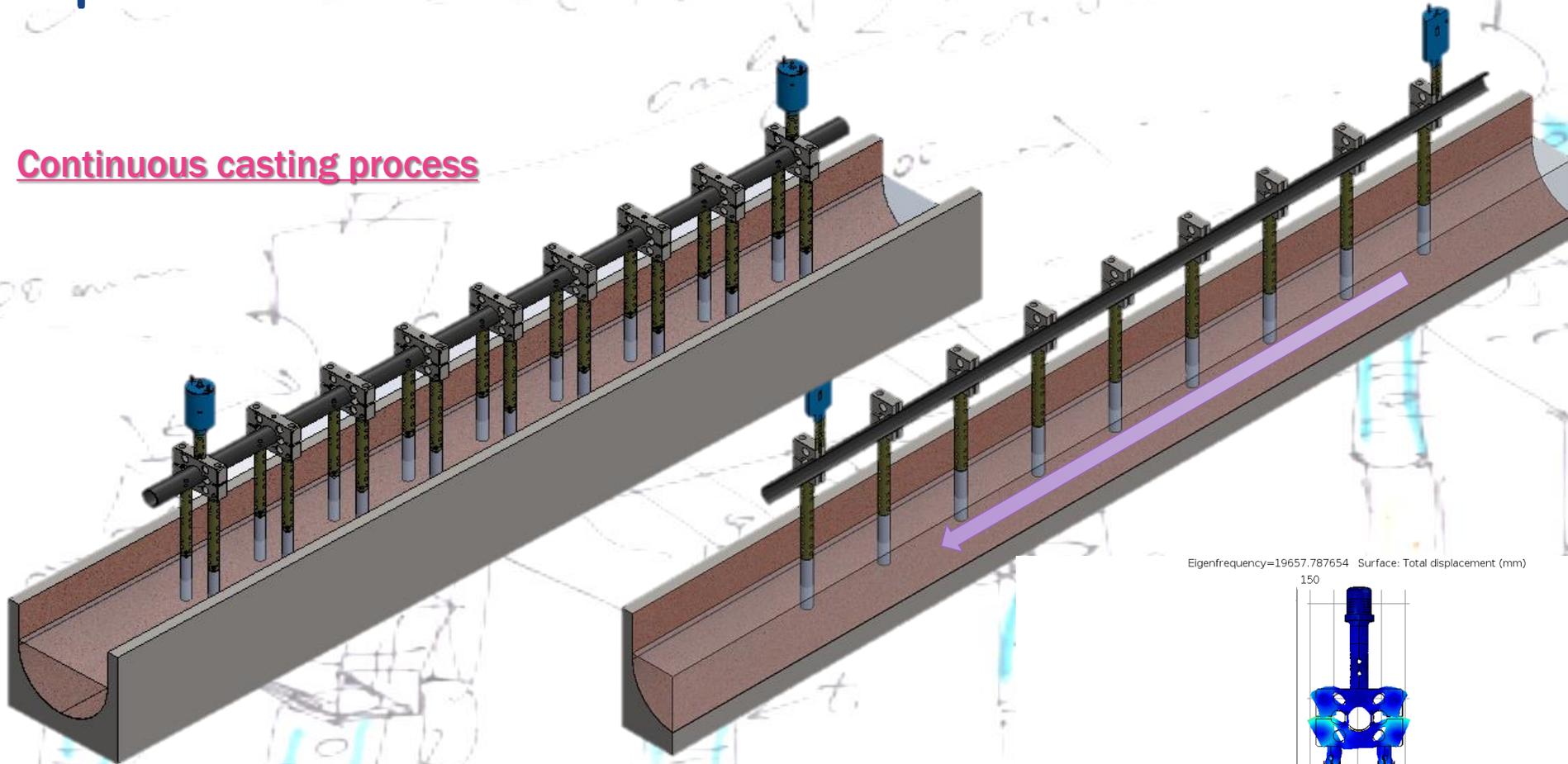
# New Advances in Continuous casting process



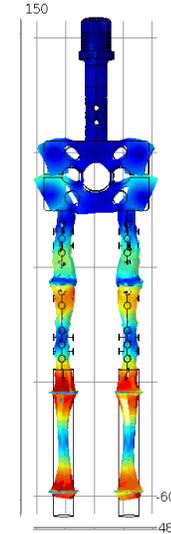
# proposal for your factory

Inventing is mixing brains and materials.  
The more brains you use, the less materials  
you need.

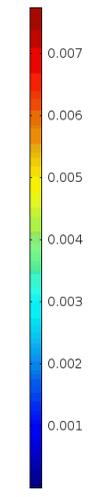
## Continuous casting process



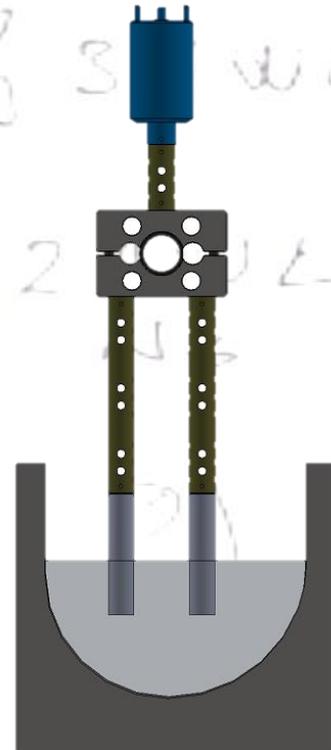
Eigenfrequency=19657.787654 Surface: Total displacement (mm)



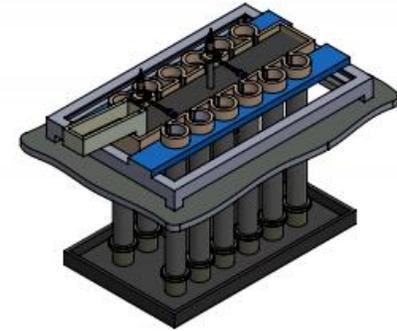
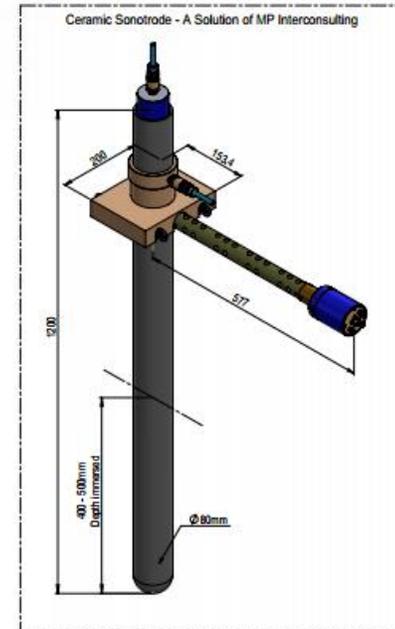
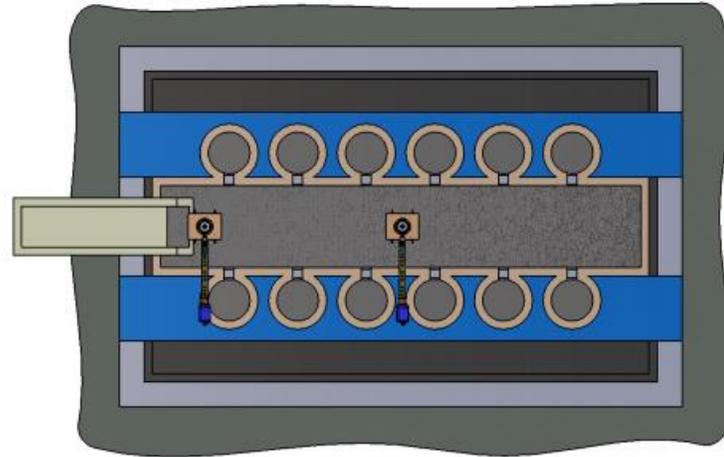
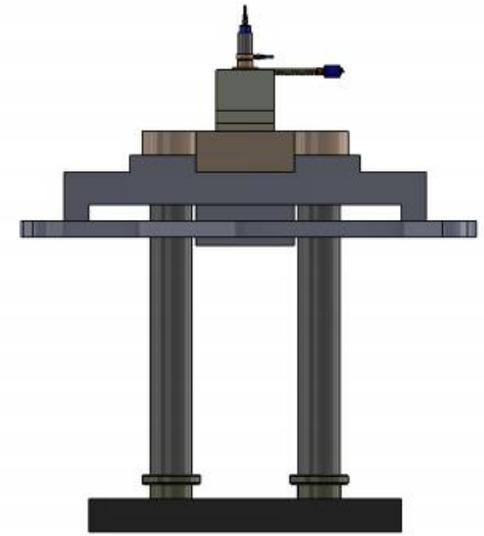
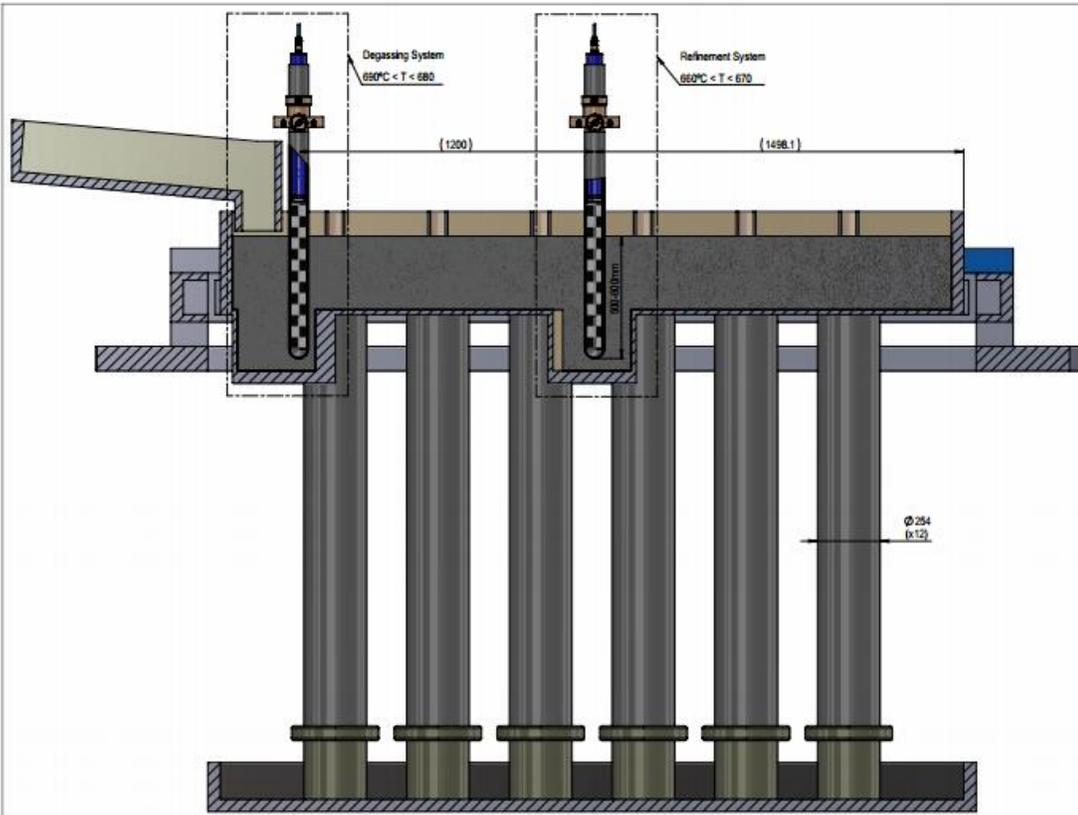
▲  $7.7319 \times 10^{-3}$



▼  $3.7471 \times 10^{-5}$

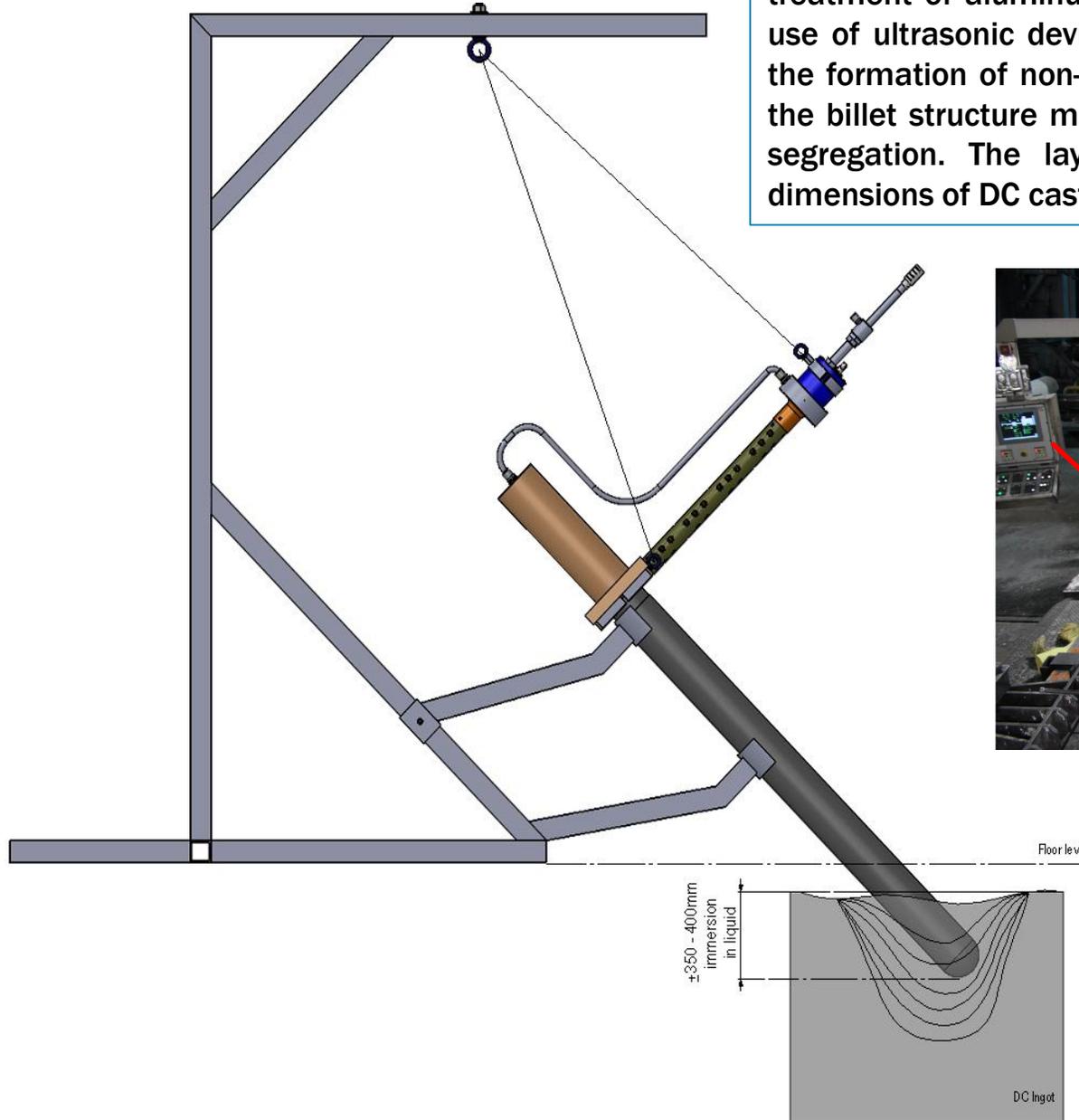


# proposal for your factory

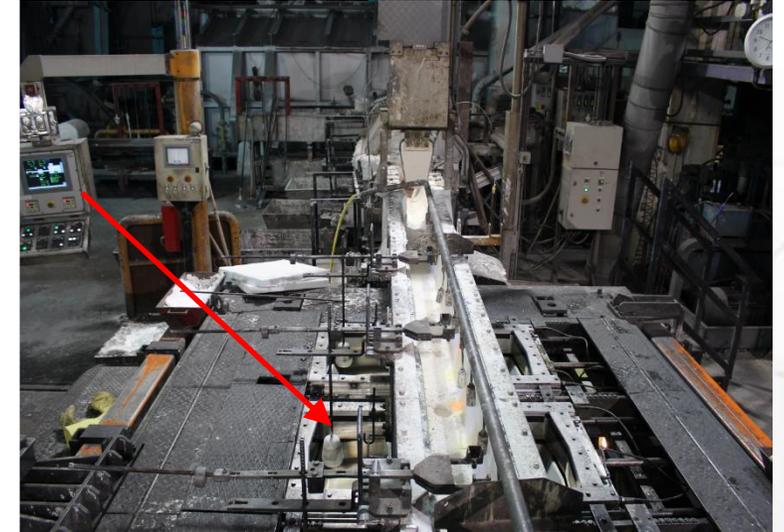


PRODUCTION	DATE	25.04.2015	STATE	3D-Modell (Rev. 0001)	REVISED
MP-PROJEKT	OBJEKT-NR.		ZEICHNUNG		
NAME	AL-FUGEN				
MP-ULTRASONICS MARKUS 30 2400 Lin. Lucia Salzburg e-mail: mpi@mpi-ultrasonics.com phone: +43 (0) 32 9314045					
General tolerance SN 258440					
Dimensional tolerances (mm)	±0.3	±0.5	±1.00	±0.5	±1.00
Surface (mm)	±0.05	±0.1	±0.2	±0.3	±0.5
Scale (mm)					AT

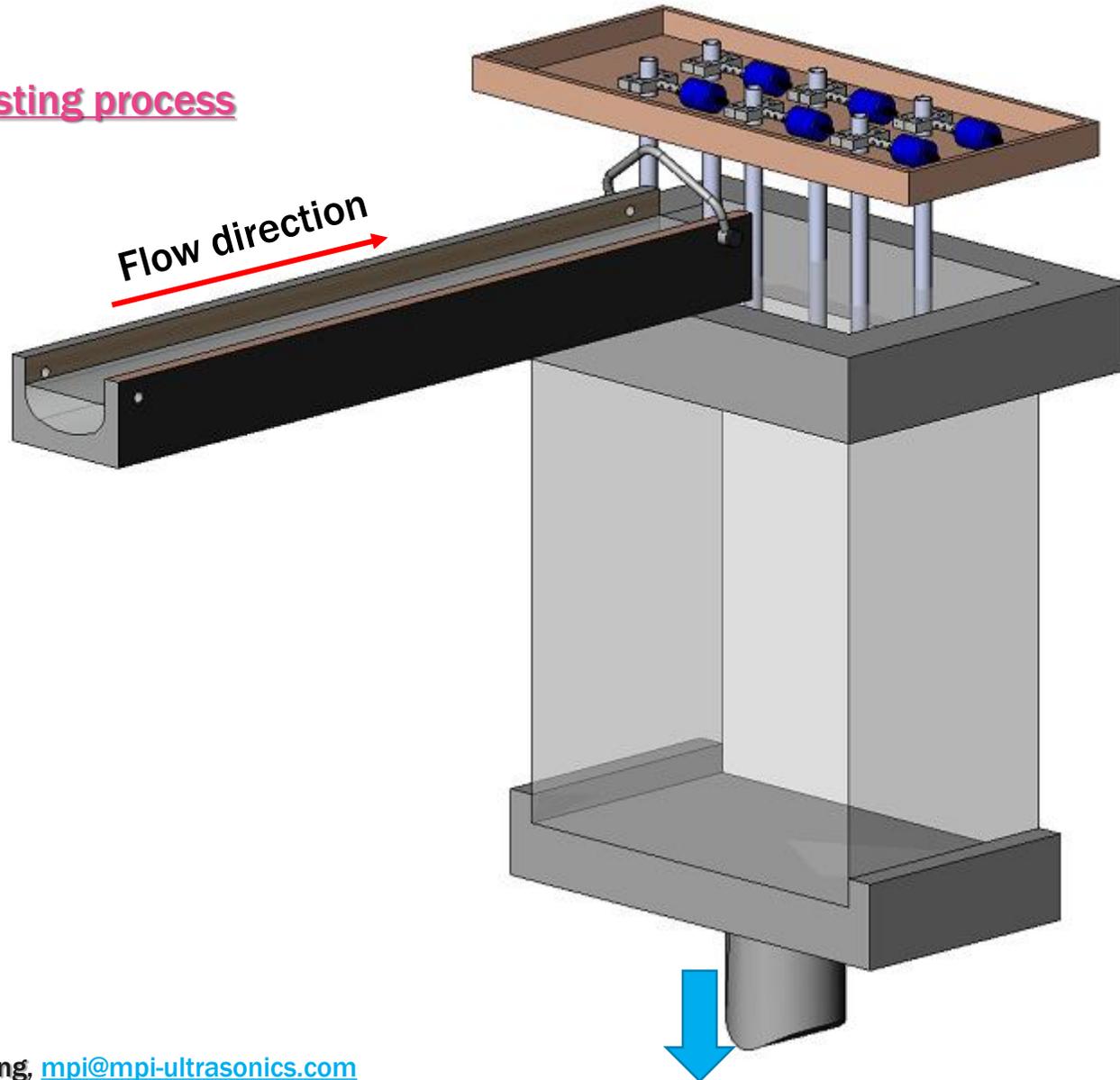
# proposal for your factory



The Figure shows the proposal of ultrasonic device to perform treatment of aluminum alloys in the sump of DC-cast billets. The use of ultrasonic device based on the MMM technology will allow the formation of non-dendritic structure during DC casting making the billet structure more homogeneous and decreasing the macro segregation. The layout proposed should be adjusted to real dimensions of DC casting equipment.

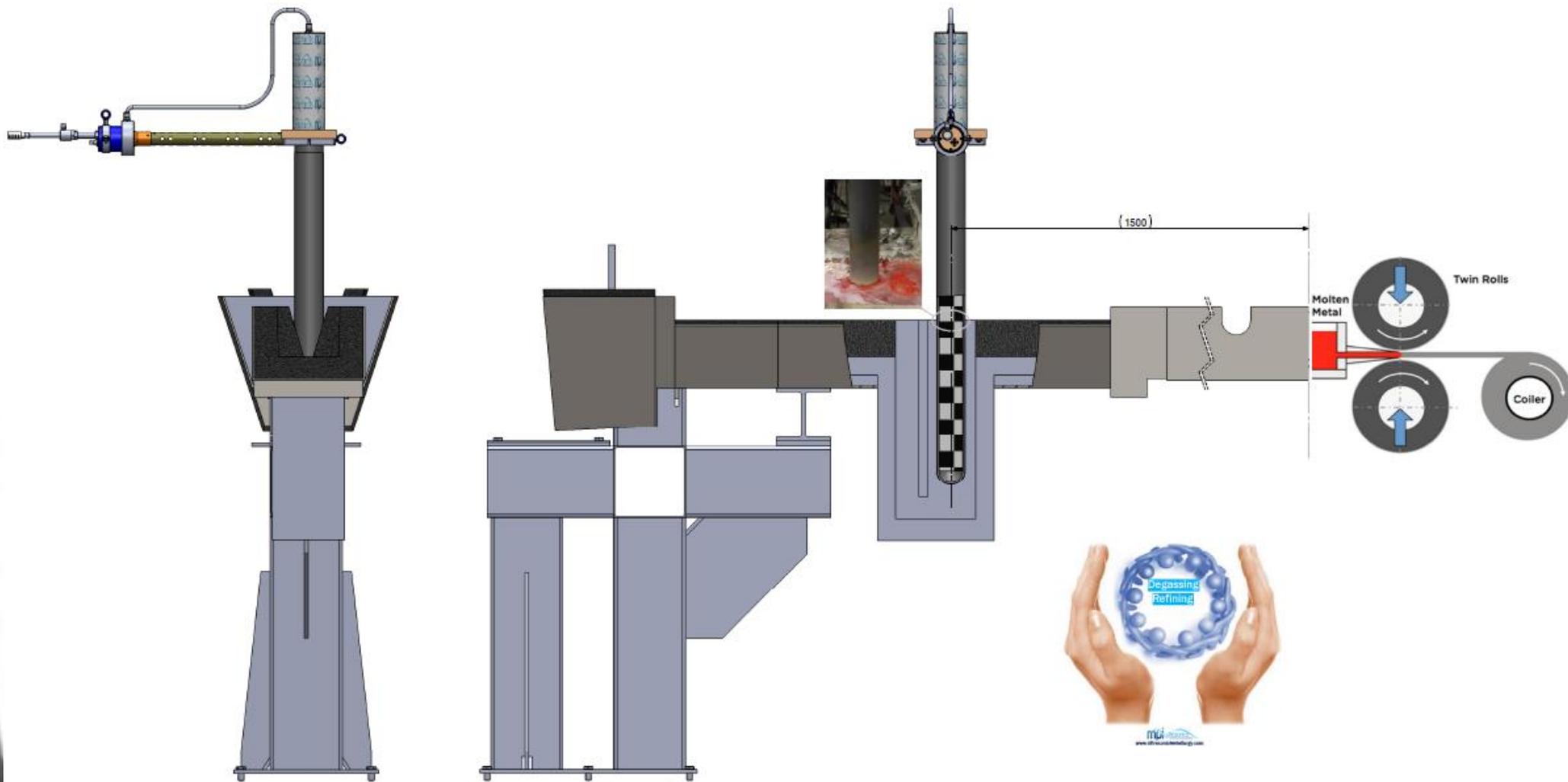


## Continuous casting process



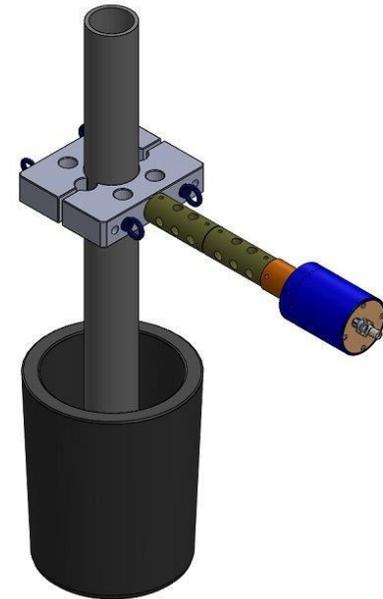
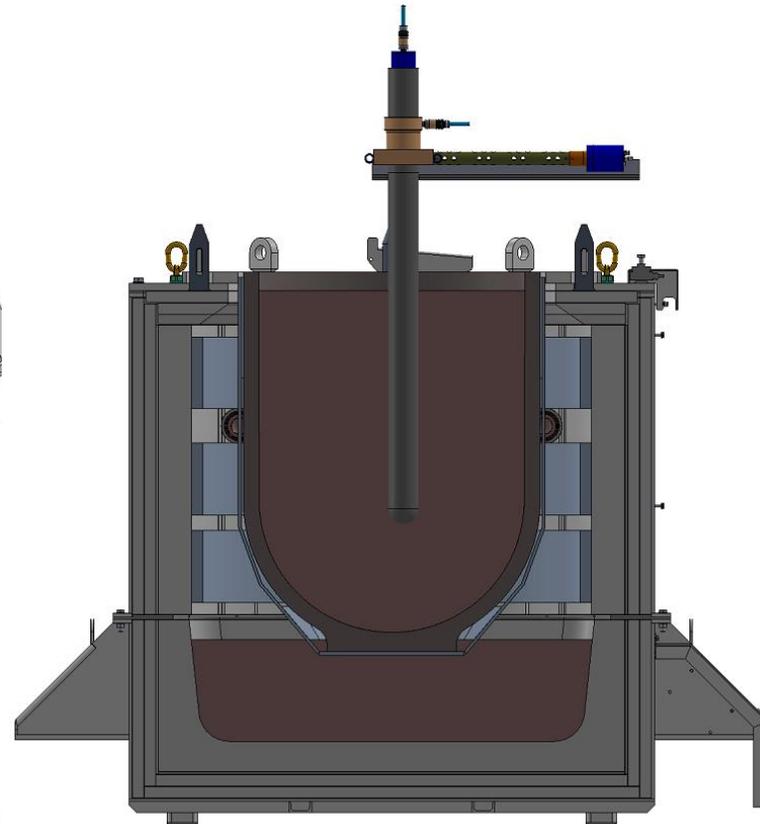
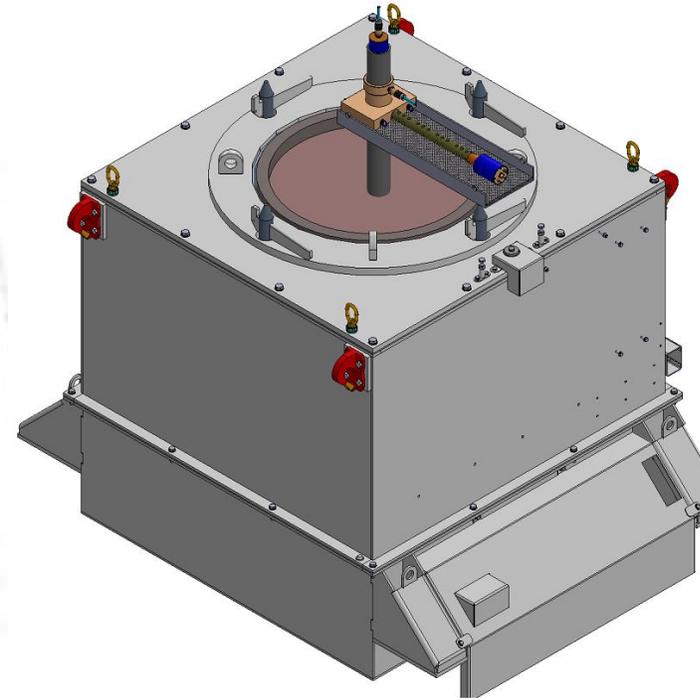
# proposal for your factory

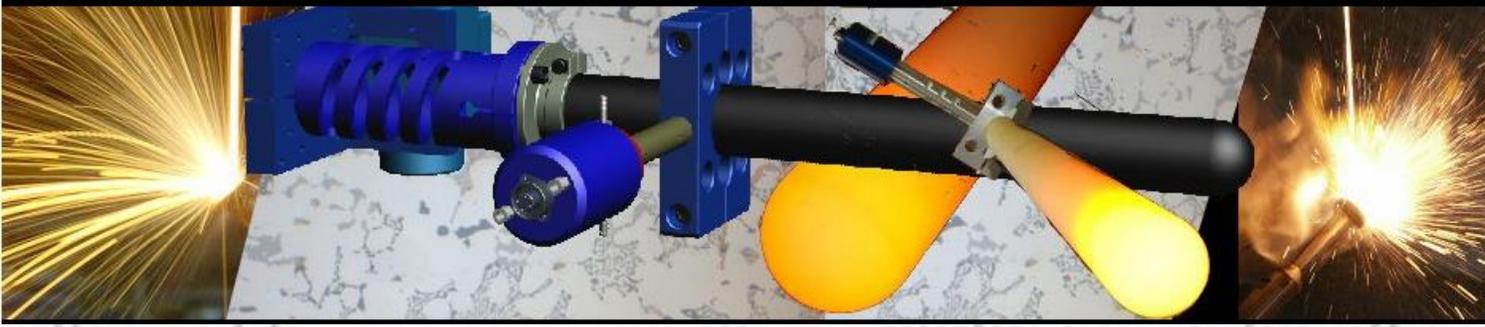
## Continuous casting process



# proposal for your factory

The Figure shows the proposal of ultrasonic device to perform degassing of aluminum alloys in a crucible.





# Ultrasonic vibrations in metallurgy...

## Cavitation

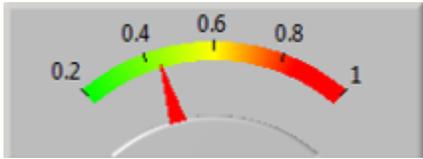
### Part 3

*No man...can choose to do what he never heard of doing  
or never thought of doing. In this sense, the ultimate  
measure of freedom is knowledge and we learn in order  
to be free.*

# Controlling Cavitation in Metallurgy

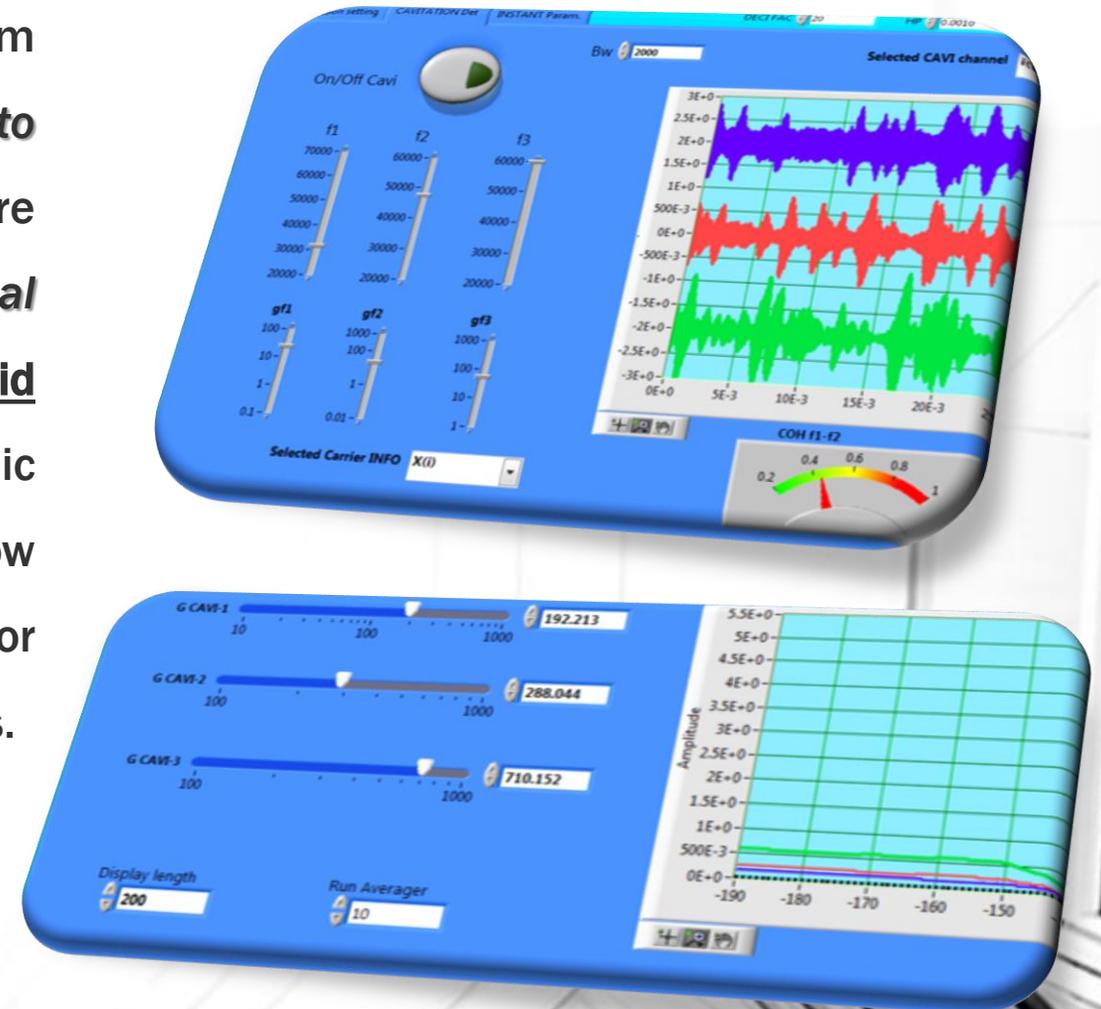
As a very powerful tool for ultrasonic liquid metals processing, we mastered real-time monitoring and measurements related to Cavitation, which is the most significant active factor for realizing number of metallurgical processing such as:

- ✓ Degassing and density increase,
- ✓ Micro alloying,
- ✓ Total surface wetting of all kind of inclusions, including blind and micro-capillary holes
- ✓ Uniform grain refinement, based on sonocrystallization,
- ✓ Extending the natural limits in alloying, mixing, homogenizing and playing with different percentages of almost arbitrarily selectable liquid ingredients.



# Controlling Cavitation in Metallurgy

Our expertise in “self-sensing techniques” developed from other ultrasonics-related *applications has opened new ways to address the cavitation measurement challenge*. Thus, we are now able “to see”, *measure and control the cavitation in real time (without submersing sensors for cavitation in a liquid metal)*. We know what the essential parameters of ultrasonic waves are in order to create and control cavitation. We know what to change, or implement during ultrasonic agitation for producing and controlling certain level of cavitation in liquids.

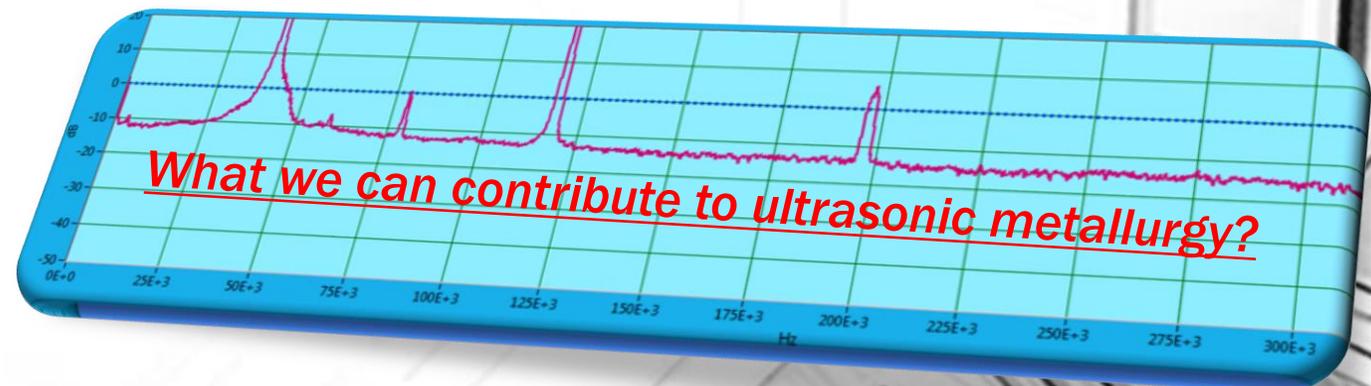


# Controlling Cavitation in Metallurgy

The active power dynamics of ultrasonic transducers is continuously monitored with modern signal processing techniques.



This involves a novel signal processing approach which is very rarely available in standard monitoring systems.



# Controlling Cavitation in Metallurgy



DSP, dedicated computer  
for real-time qualification  
and quantification of  
cavitation.

Based on specific Lab View,  
multi-windows and real  
time monitoring software.

## Self-sensing technique

We can make diagnostic and measurements of cavitation without submersing any kind of sensor, where the ultrasonic source (sonotrode and ultrasonic converter) is in the same time emitter of ultrasonic waves, and active sensing element for acoustic activity and cavitation related signals.



# Controlling Cavitation in Metallurgy

We know **exactly and precisely which signal processing** and modulating parameters should be applied to a carrier ultrasonic signal (from ultrasonic power supply) in order to control certain level of cavitation in a liquid metal.

We achieved to **extract pure acoustic** (and electric) signals related only to cavitation, from overall and mixed acoustic field activity (apart from high amplitude carrier ultrasonic signal, separated from surrounding mechanical, low and higher frequency harmonics, which are not related to cavitation). We can monitor power of cavitation, and different amplitude and phase, real-time and frequency dependent parameters, as well as values based on complex mathematical calculations, and based on such parameters we can actively control ultrasonic power supply (generator) in order to keep desired level of cavitation continuously (during ultrasonic processing of liquid metal).

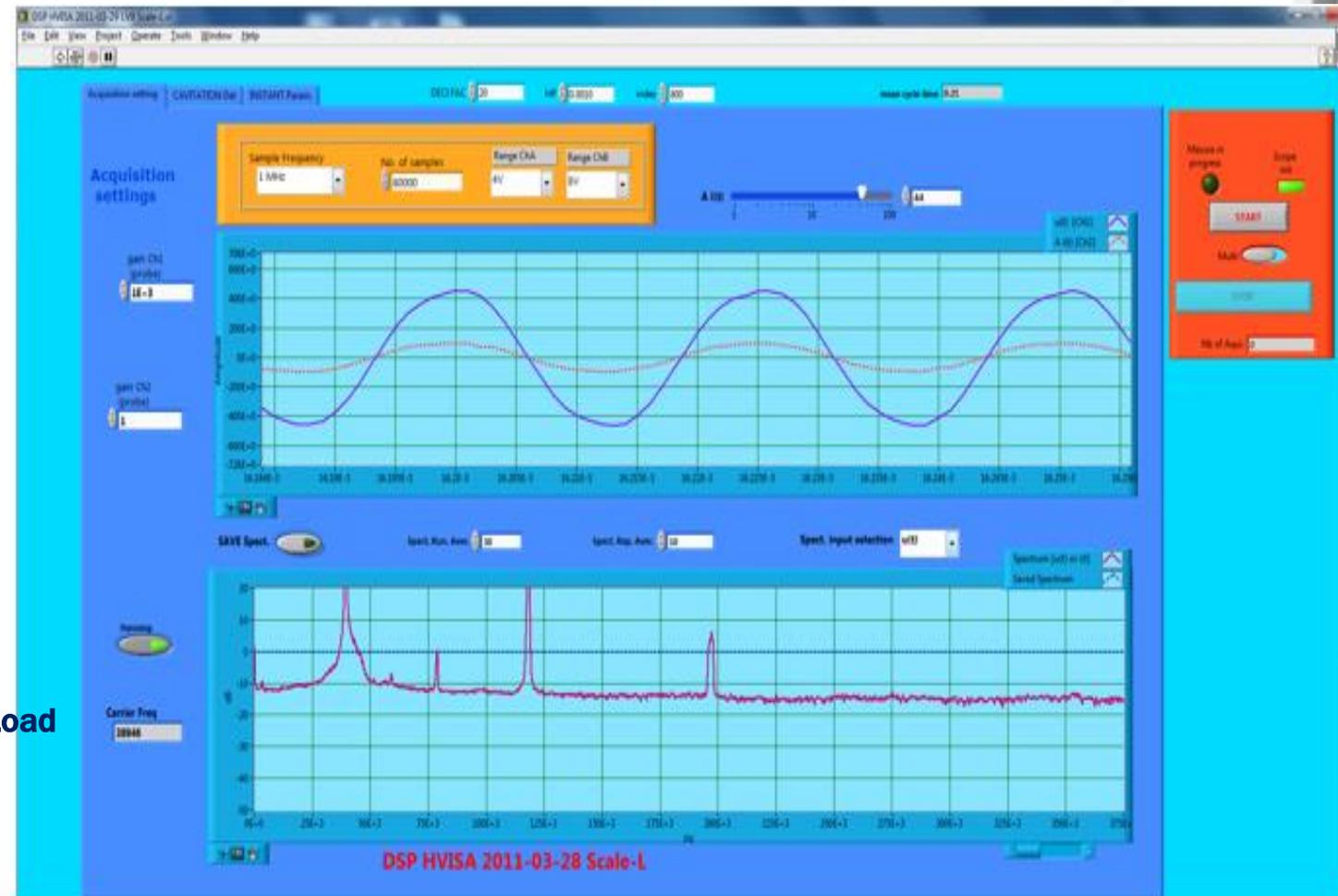
# Controlling Cavitation in Metallurgy

Computerized station with specific software performing advanced signal processing methods that are applicable in acoustics and ultrasonic technologies for detection and characterizations of multilevel modulated (ultrasonic) signals.

Visualize and measure real-time and frequency dependent plots of immediate

- ✓ active and apparent (ultrasonic) power,
- ✓ different signal amplitudes (vs. time & frequency)
- ✓ immediate signal frequency versus time,
- ✓ Actual, high power, load impedance.

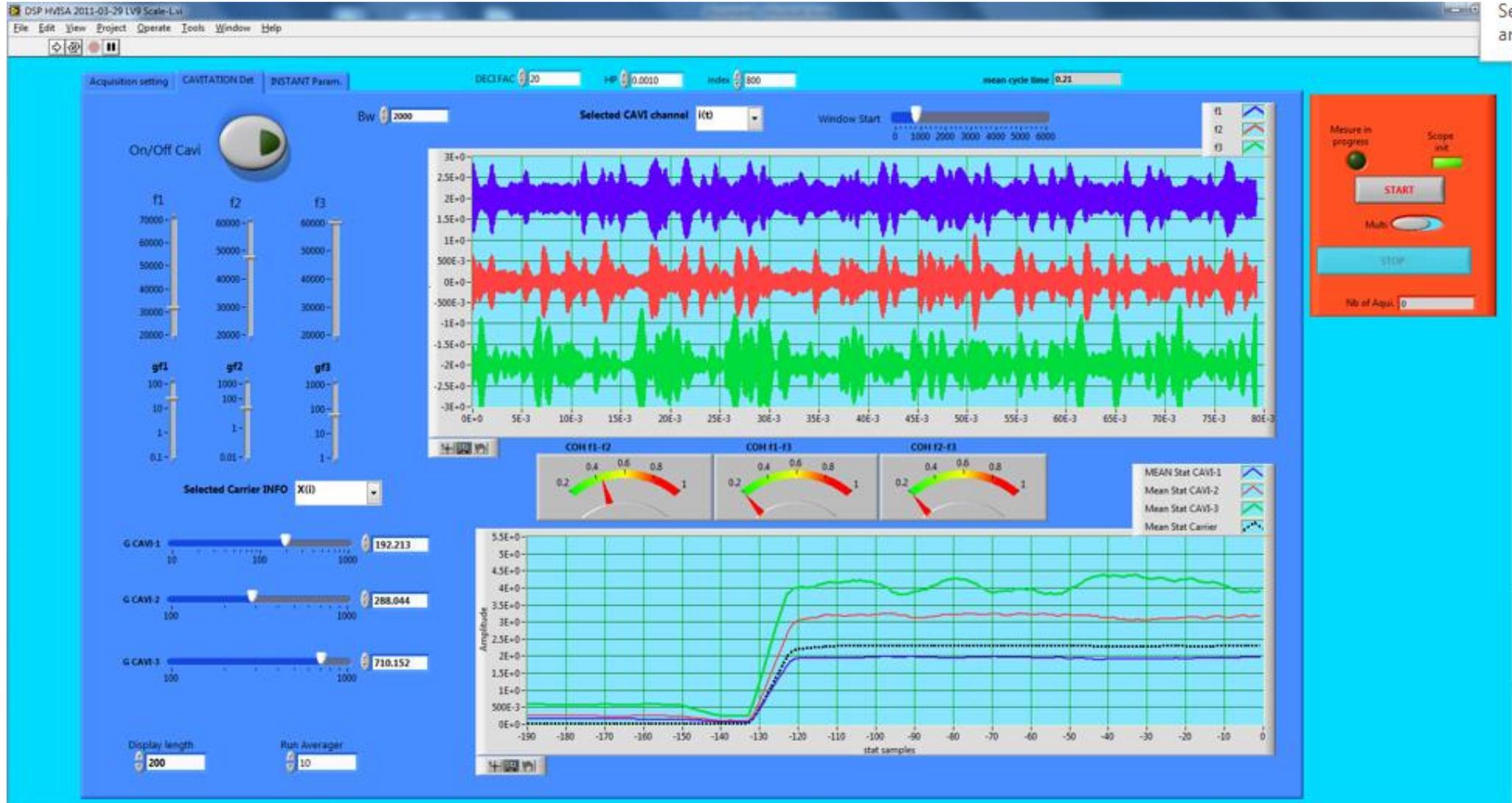
**Amplitude – Frequency Spectrum (of Load current and voltage signals during ultrasonic processing)**



# Controlling Cavitation in Metallurgy

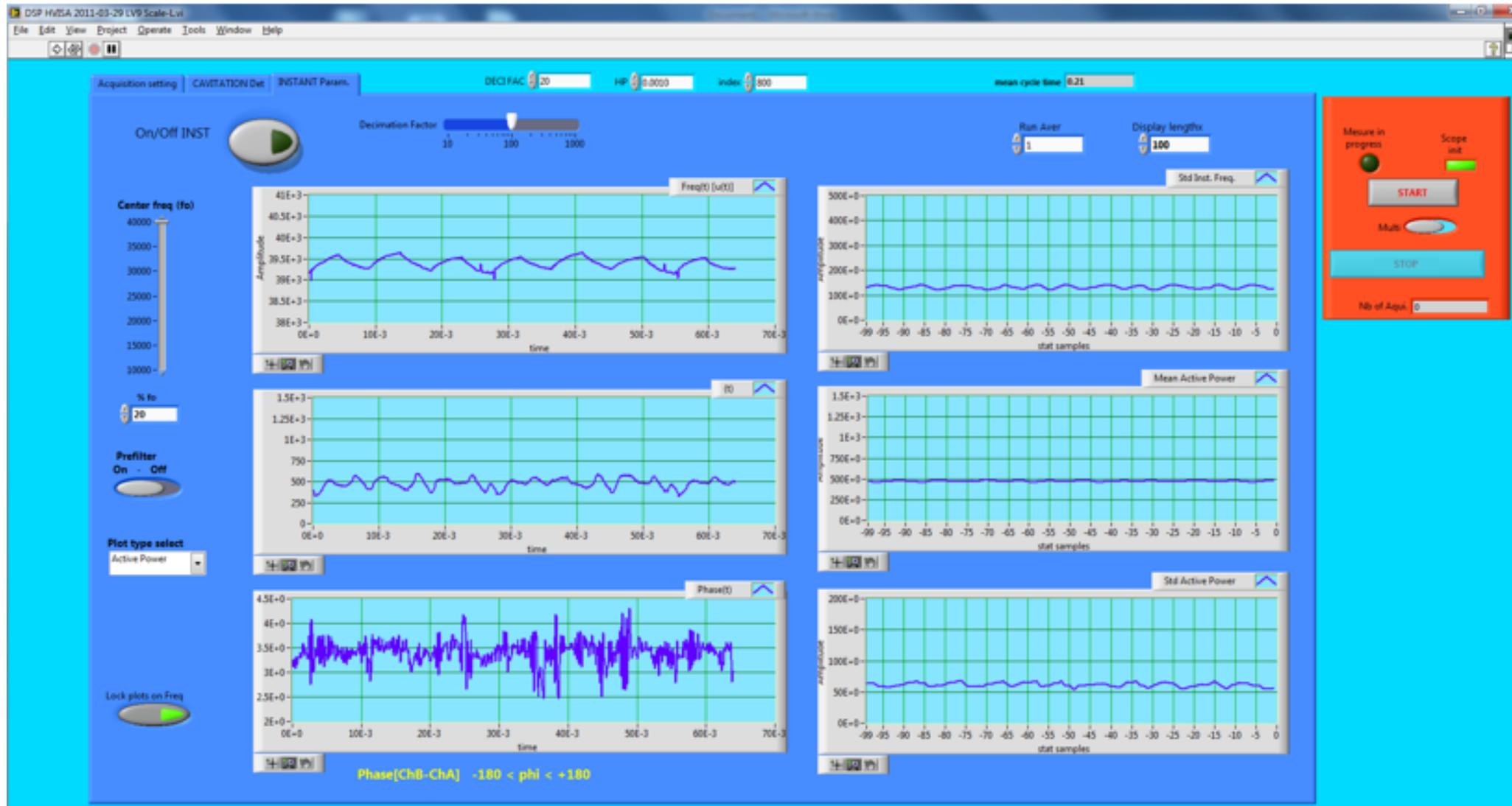
Another significant message is that present measurements related to ultrasonic liquids processing (known from literature, and industrial practices) are far below from what is enough, if we would like to master, qualify and quantify what modern ultrasonic liquids processing is (applicable to Sonochemistry, liquid metals processing, degassing, Sonocrystallization). **Our approach is giving chances to generate real-time feedback (during ultrasonic processing) and to stimulate the most important time and frequency domain parameters of ultrasonic field (based on knowing what is really happening in acoustically agitated media, and what should be maximized in real time)... what nobody is presently addressing.**

# Controlling Cavitation in Metallurgy



Measured amplitudes of Cavitation in a time domain, and after averaging

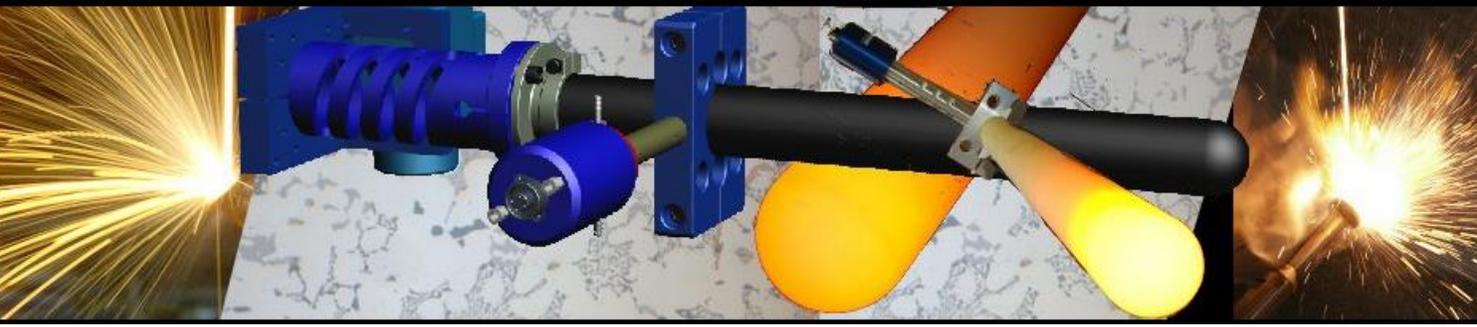
# Controlling Cavitation in Metallurgy



Operating Frequency, Power and Phase in a time domain (left) and after averaging (right)

# Controlling Cavitation in Metallurgy

- ✓ Our development in this domain took almost 10 years of work.
- ✓ Looks that there is nothing comparable to what we are offering as an integrated package of multilevel signal analysis (for acoustics and complex ultrasonic signals analysis... and with much wider fields of future applications).
- ✓ Dynamic, almost non-stationary, randomized and time-variable, pulse-repetitive, and phase-frequency modulated ultrasonic waves are producing strongest effects of cavitation and realizing spatially uniform, ultrasonic liquids processing.



[www.UltrasonicMetallurgy.com](http://www.UltrasonicMetallurgy.com)

**Thank You.**

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[mpi@mpi-ultrasonics.com](mailto:mpi@mpi-ultrasonics.com)