

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

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MMM Technology applied to Static, DC and CC casting process

MMM Technology was developed by MP Interconsulting. 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.

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1. Introduction

Ultrasonic MMM technology, when operating above the cavitation threshold is promoting numerous low pressure (almost vacuum) bubbles in a liquid metal, which start growing, pulsing in a continuous expansion/compression regime and finally collapse. Ultrasonic **MMM processing** applied to non-ferrous alloys' melt treatment can result in metals purification, microstructure refinement, structure modification, (better and faster melt homogenization, optimized alloying and micro alloying, wetting of non-metallic inclusions, and significant alloy density increase) and degassing, based on the specifically created acoustic field introduced in a molten metal in order to create spatially and uniformly well distributed and wideband multi- frequency cavitation.

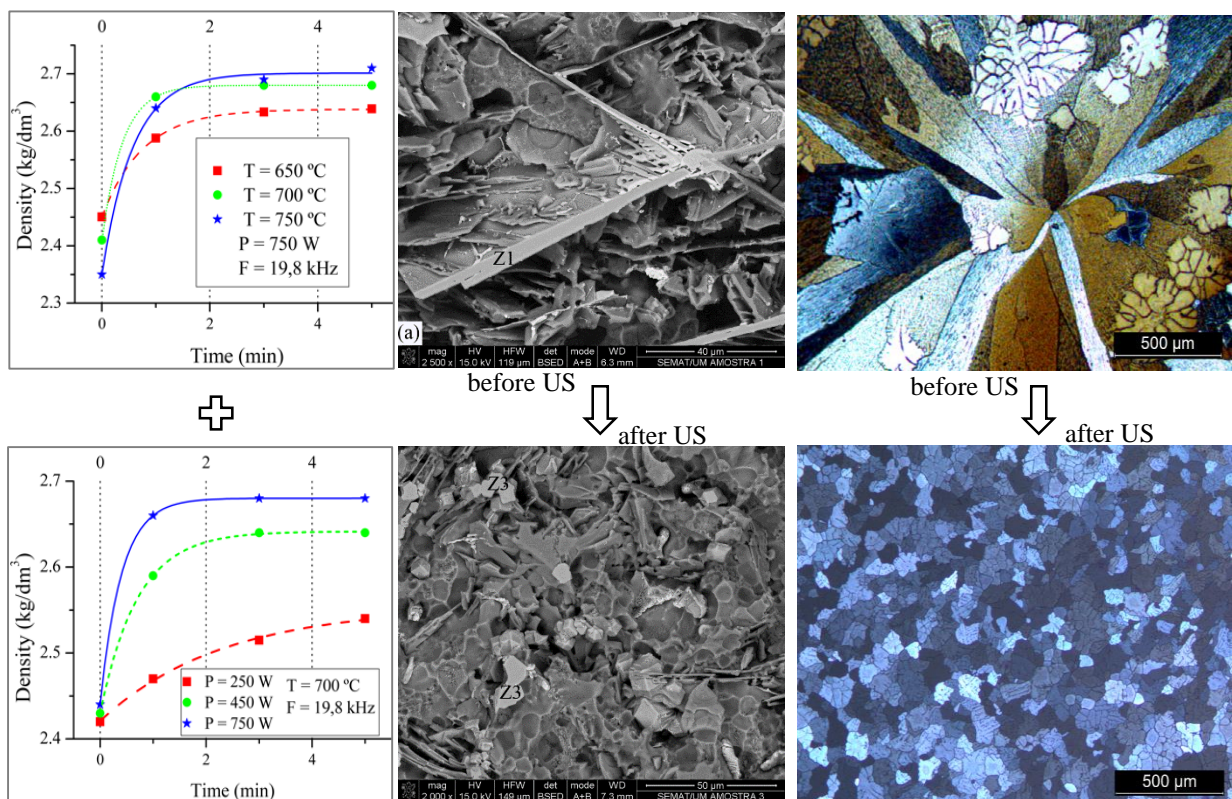
When a liquid metal is exposed to high intensity ultrasonic vibrations, the alternating pressure above the cavitation threshold creates numerous cavities in a liquid metal promoting two effects:

(1) Degassing effect: Cavitation produced by ultrasonic MMM technology intensifies mass (and heat) transfer processes and accelerates the diffusion of hydrogen from the melt by developing low pressure cavitating bubbles that are collecting hydrogen. As acoustic cavitation progresses with a time, adjacent bubbles mutually touch and coalesce, growing to a size sufficient to allow them to rise up through the liquid, against gravity, until reaching surface. Degassing is easier and faster if melt temperature is higher than optimal temperature for grain refinement, but on such high temperatures microstructure refinement is not effective.

(2) Microstructure refinement and grains modification effect: the alternating pressure achieved by MMM ultrasonic processing of liquid metal is creating cavitation bubbles able to absorb kinetic (thermal motion) energy in a melt, undercooling the liquid metal at the bubble-liquid interface, resulting in nucleation on bubble surfaces. When bubbles collapse acoustic micro streaming develops in the melt, distributing initially created nuclei into surrounding liquid producing significant number of new nuclei in the molten alloy, thus promoting heterogeneous nucleation. Microstructure grain refinement for every alloy has its optimal temperature, which is significantly lower compared to optimal degassing temperature (and should be found before starting real production and technological testing). Operating as closer as possible near liquidus temperature curve will produce finer and denser grain structure, but we also need to satisfy real casting conditions and keep liquid metal temperature sufficiently high, meaning that optimal and compromising temperature should be experimentally found (before applying ultrasonic processing in a production line).

MMM sonic and ultrasonic technology is a reliable technique for melt treatment that has been developed and applied in different non-ferrous alloys. Based on the results achieved from different alloys and according to results obtained in a laboratory and industrial scale, the main conclusions that can be drawn are:

- (1) Ultrasonic degassing can be an efficient process to degas molten non-ferrous alloys. For melting charges in static conditions (industrial scale) acceptable degassing is achieved after 2 minutes ultrasonic treatment, although after 1 min the alloy density is already up to 90% of the maximal value.
- (2) When compared with the traditional fixed-frequency ultrasonic sources MMM ultrasonic technique seems to improve significantly ultrasonic degassing process by increasing the final alloy density and degassing rate.
- (3) Ultrasonic processing by MMM technology is an external supply of acoustic energy – presenting physical process - environmentally clean and efficient that can promote refinement of primary grains and intermetallic phases, modification of eutectic Si, and decrease of porosity in non-ferrous alloys.
- (4) Ultrasonic treatment clearly improves mechanical properties and the fluidity of treated alloys.



Examples of US processing results: degassing, intermetallic refinement and grain refinement.

2. Research and Development

This document is created to facilitate fundamental understanding of ultrasonic energy effects on liquid metals processing – based on MMM technology, specifically on degassing and refinement of liquid nonferrous metals, including practical advices based on our recent studies.

Hydrogen precipitates as porosity during the solidification of aluminum alloys and is detrimental to mechanical properties of aluminum alloy castings. Reducing porosity during casting is still a challenging problem in aluminum industry. Traditional techniques based in rotary degassing (that uses finely dispersed argon), or based in chlorine waffles are used to degassing. However, these techniques presents a median efficiency and have trends to create environmental problems. Apart from the problems arising from the presence of the hydrogen, the non-ferrous alloys are prone to achieve heterogeneous structures, usually dendritic, requiring suitable melt treatment to reduce and control the grain size, homogenize the alloys, modify the intermetallic and so on. Therefore, controlling the microstructure of non-ferrous alloys is of primary importance to achieve high mechanical performance, thus requiring suitable degassing, refinement and modification.

Our research of degassing based in MMM have showed that it is possible to achieve high efficiency of degassing and grain refinement in aluminium and magnesium alloys. The research focused on validation of MMM technology on the melt treatment, exploring the different operating parameters as well as different alloys.

Currently, with our continuous research and developments, for each kind of casting process (i.e: static casting in crucible, CC casting or DC casting), we can offer a different approach. These approaches are designed by aggregating relevant and multidisciplinary knowledge of Metallurgy, Mechanics and Electronics. The combination of these knowledges allows to build and readapt MMM technology to different casting practices.

For ultrasonic degassing, considering variety of casting options it is necessary to know:

- (i) What is your casting process where ultrasonic degassing will be installed?
- (ii) What are your raw-materials?
- (iii) What are the conventional operation conditions? i.e. temperature, volume of melt...
- (iv) What are expected objectives and limits? Should be realistic.

Thus, for each client and according to basic (factory) conditions of a casting process, the project should respect the following steps:

(1) Perform preliminary tests in a laboratory to demonstrate the applicability of MMM technology in used melt alloys, and establish operating limits that are fundamental for following steps (meaning: going directly to a production casting line without preliminary laboratory testing should be excluded, and it is highly not recommendable).

(2) Within laboratory established operating limits, apply the ultrasonic device on degassing of non-ferrous alloys in real process conditions. Of course, ultrasonic equipment should be conveniently modified and adjusted to fit existing casting line, and certain modifications should be implemented on a casting line in order to facilitate ultrasonic processing. This is highly professional design process (not just simple implementation).

(3) Experiment certain time directly with a production line in order to find the best operating conditions regarding ultrasonic controls, casting line and used alloy, this way formulating the working guidelines for maximizing results of degassing process.

For ultrasonic grain refinement, considering variety of casting options it is necessary to know:

(i) What is your casting process where ultrasonic grain refinement will be installed?

(ii) What are your raw-materials?

(iii) What are conventional operation conditions? *i.e.* temperature, volume of melt...

(iv) What are expected objectives and limits? Should be realistic.

Thus, for each client and according to basic (factory) conditions of a casting process, the project should respect the following steps:

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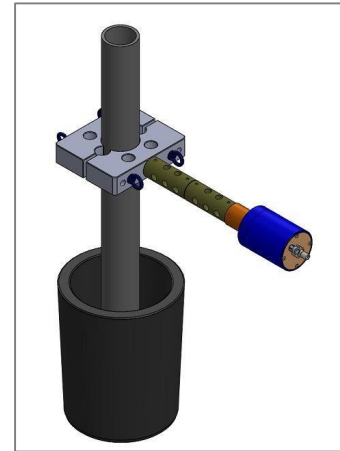
(3) Experiment certain time directly with a production line in order to find the best operating conditions regarding ultrasonic controls, casting line and used alloy, this way formulating the working guidelines for maximizing results of degassing process.

Although the results obtained through the application of MMM ultrasonic technology in different process conditions have showed the potential of degassing and refinement of aluminium and magnesium alloys, it is recommended that developed technology should be preliminarily evaluated on the alloys and process in a user company before making a commitment to it. There is no magic, immediate and miraculous ultrasonic processing that will produce optimal results without mentioned preparatory and optimization steps.

3. Laboratory testing in crucibles (static conditions)

In order to perform laboratory testing to evaluate the capability of ultrasonic degassing and grain refinement of non-ferrous alloys by MMM technology, several considerations should be taken into account:

The introduction of ultrasonic energy into a melt requires an ultrasonic transducer and an ultrasonic power supply (or generator). On the webpage: <http://www.UltrasonicMetallurgy.com/>, it is possible to see relevant information and set of relevant products available to perform the tests.



Experimental setups to test ultrasonic processing on non-ferrous alloys can be built according to your needs and objectives. Thus, it is necessary to have:

- (1) Ultrasonic Generator based on MMM Technology
- (1) Piezoelectric transducer tolerant to fast signal modulations (usually 20 kHz)
- (1) Set of clamp-on sonicator parts for melt degassing
- (1) Composite ceramic or metal tube resonator for melt degassing
- (1) Solid metal sonotrode for grain refinement (homogenization, alloying...).

The experiments should be carried out in two independent groups or setups: (1) Degassing and (2) Refinement (because for degassing we need significantly higher melt temperature than for grain refinement).

(1) Degassing

In order to investigate ultrasonic degassing, different batches of Al alloy should be sequentially degassed by ultrasonic MMM technology. **(i)** An electro-resistive heating furnace (between 2 to 10 kg), equipped with a SiC–graphite–clay crucible, can be used to melt the alloy. **(ii)** After stabilizing operating temperature, molten melt must be ultrasonically degassed, as a parametric function of melt temperature of batches, and based on different degassing time intervals. In addition, a positioning device that supports the US unit and controls its relative position to the surface of the molten alloy should be used. **(iii)** After each degassing test pre-established in test

protocol (for instance, like presented in the table 1, below), the treated sample should be poured in a thin-walled iron cup and allowed to solidify under a reduced pressure of 60 mm Hg.

Table 1

Use the RPT test to evaluate the hydrogen content of sample, it is assumed that every porosity in the sample is due to hydrogen.

<i>Alloy</i>	<i>Temperature [°C]</i>	<i>Time [min]</i>	<i>Frequency [kHz]</i>	<i>N° of Samples [-]</i>	<i>Observations</i>
...

Each density result is the average of (N°) number of samples. RPT samples should be taken for each processing time interval. Degassing efficiency η will be calculated using the following equation, where D is the theoretical alloy density, and D_i and D_f are the initial and final alloy densities, respectively

$$\eta = \frac{D_f - D_i}{D - D_i} \times 100$$

(2) Refinement

The experimental laboratory set-up used to perform grain refinement of aluminium alloys consists of ultrasonic equipment as mentioned above for ultrasonic degassing. Only refinement sonotrode could be different.

- (i) The alloy must be melted and held inside the crucible at different temperatures established during 15 - 30 minutes in order to rich homogenization.
- (ii) Molten alloy should then be slowly cooled until the pre-established US processing temperature.
- (iii) For every set of experimental conditions, US vibrations must be applied isothermally during 30-60 seconds. Then, the US unit should be removed, the melting crucible taken out of the furnace and the molten alloy poured in a steel die pre-heated at 250 °C, or in a sand mold.
- (iv) For the sake of comparison experiments (with control samples) must also be carried out without ultrasonic treatment.

(v) Samples for microstructure characterization must be taken from each cast sample, and then cut, grinded and polished up to 1 μm (using 1200 SiC paper). Such samples for optical microscopy characterization should be etched using specific reagent (according to alloy) to reveal the resulting microstructure. (vi) Phase identification and chemical composition must be evaluated by quantitative EDS analysis using a high resolution a Scanning Electron Microscope. (vii) For tensile testing, the specimens should be machined from the cast samples respecting standardized shapes and conditions.

Additionally, continuous US agitation applied on melt during cooling can be used, for instance in sand casting processes. During melt pouring in a sand mold cavity, US agitation can be successfully used to refine and modify alloy microstructure.

In order to realize such US processing, it is necessary to accommodate mold cavity and create a place where US vibrations can be introduced (for instance, to use the melt feeder hole as the place where sonotrode tip will enter).



Ultrasonically assisted melt degassing and refinement should be understood as the main objectives, i.e, during each of them, the associated and arising phenomenology is very complex, where, for instance, a small shift in temperature could present a high impact on the final process efficiency. Thus, the foundrymen interested to use this technology must be prepared and feel comfortable to proceed with necessary adjustments in the process within the operating limits allowed by different equipment and products.

Here, in order to efficiently apply ultrasonic processing, the preexistence of highly professional knowledges in areas as Metallurgy, Mechanics and Electro-mechanics is mandatory. Why? Because, this technology is based on the integration of two type of parameters: (1) parameters related to number of metallurgical aspects (*i.e.*, temperatures, chemical composition of alloy, and so on.); and (2) operational parameters which concern everything that is related to applied ultrasonic technology. So, the limits of metallurgical and mechanical parameters should be understood, matched and adjusted with the objective to improve the process performances. The ultrasonic technology will not be as *add-on* to the process, but it should rather be an integral part of the process. There isn't a ready-made, universal DEMO equipment that can be applied

in every casting house. Every casting house should first analyze and understand the problem, perform some preliminary tests, and build customized ultrasonic equipment for a targeted processing.

When speaking about ultrasonically assisted degassing it is important to understand that such degassing is very significant, because this also means to clean the molten metal. This is more than only to remove a hydrogen dissolved in liquid metal; in the same process we remove or neutralize impurities and nonmetallic inclusions, and improve the homogeneity and density of melt. Moreover supplied acoustic energy activates the liquid metal, what is extremely important and beneficial for mold casting concerning metal fluidity.

Ultrasonic degassing is based on the cavitation, i.e, the production of cavitation bubbles in melt is the root of success. But, how we can create dense, uniformly distributed and efficient cavitation should be mastered? Theoretically we can offer simple answers, but practical application-related answers to such questions is the key of success of ultrasonic treatment. To reach high performances in ultrasonic degassing it is necessary to study, experiment and create a correct protocol of testing. Then, technology user will be ready to apply ultrasonic degassing based on MMM technology.

Useful effects of ultrasonic melt processing are related to efficient transformation of electric energy (using ultrasonic power supply or generator) to mechanical vibrating energy of ultrasonic transducer (operating in resonance), which is in the last step radiated to a liquid metal, while creating cavitation bubbles, stimulating ultrasonic capillary effects and making acoustic streaming and alternating vibratory agitation. In this process we need to minimize thermal losses (in ultrasonic generator, transducer and sonotrode) and maximize real load power of acoustic energy given to a liquid metal. In the same time we may need to make proper signal modulations (amplitude, frequency, phase and pulse-width modulations) in order to maximize mentioned effects and cavitation, what is effectively realized based on MMM technology. The integration of ultrasonic processing in casting process will dramatically increase the integrity and mechanical properties of alloy castings. Furthermore, current results are showing that when the process is under control, it is possible to scale up the production, what is leading to cost reduction, energy savings, and other benefits.

Performances of casted parts are affected by soundness, sanity and metal matrix structure, meaning that chemical and mechanical homogeneity, good degassing, grain refinement, and/or modification of intermetallic and silicon eutectic compound, should be achieved. Essential in having success of ultrasonic melt processing is to control the melt temperature. We could say that for aluminum grain refinement it is necessary to operate in temperature range between 630 to 660°C, but this is only approximately correct, since optimal temperature depends on specific alloy, on melt volume, geometric relation sonotrode/crucible and parameters and spectral content of applied ultrasonic radiation. It is also important how ultrasonic energy will be delivered to a liquid metal; for instance during melt cooling, or keeping isothermal conditions during certain time. These two ways of ultrasonic processing (on different temperature regimes) are producing different results due to importance of specific temperatures for realizing specific reactions of involved chemical elements.

The choice of processing temperature regime should be properly selected (by the production objectives, type of processing, and by getting operational benefits).

Regardless of the treatment process (such as degassing or refinement etc.), it is good practice to perform chemical characterization of the alloy; for instance DSC analysis (Differential scanning calorimetry). With this type of analysis it is possible to quantify different chemical reactions and temperatures at which reactions occur. These temperatures will be a good indicative information to customize ultrasonic treatment.

4. Useful comments for new users of ultrasonic processing

(1) The worst case scenario regarding ultrasonic aluminum processing is in cases of aluminum recycling. Many producers of aluminum alloys are using old, scrap, polluted and waste aluminum for melting and recycling. Such raw material quality is not stable, not representative, and not easy for any kind of efficient metallurgical processing and casting. Such users would like to make one-step ultrasonic processing and make high quality aluminum of it, but this is too optimistic, or not possible. Since before every (new) introduction of ultrasonic processing in certain metallurgical line, we need to make parametric laboratory characterization of every specific alloy that will be treated (regarding operating degassing and grain refinement temperatures, as well as to determine liquidus and solidus curves and proper processing time intervals). With much polluted, scrap aluminum as a raw material, proper, stable and reliable parametrization (or characterization) is not possible, because input materials are always different. It is absolutely excluded that we make ultrasonic processing in such situations. Later, after number of additional technological steps we could discuss how and where to apply ultrasonic processing in such situations.

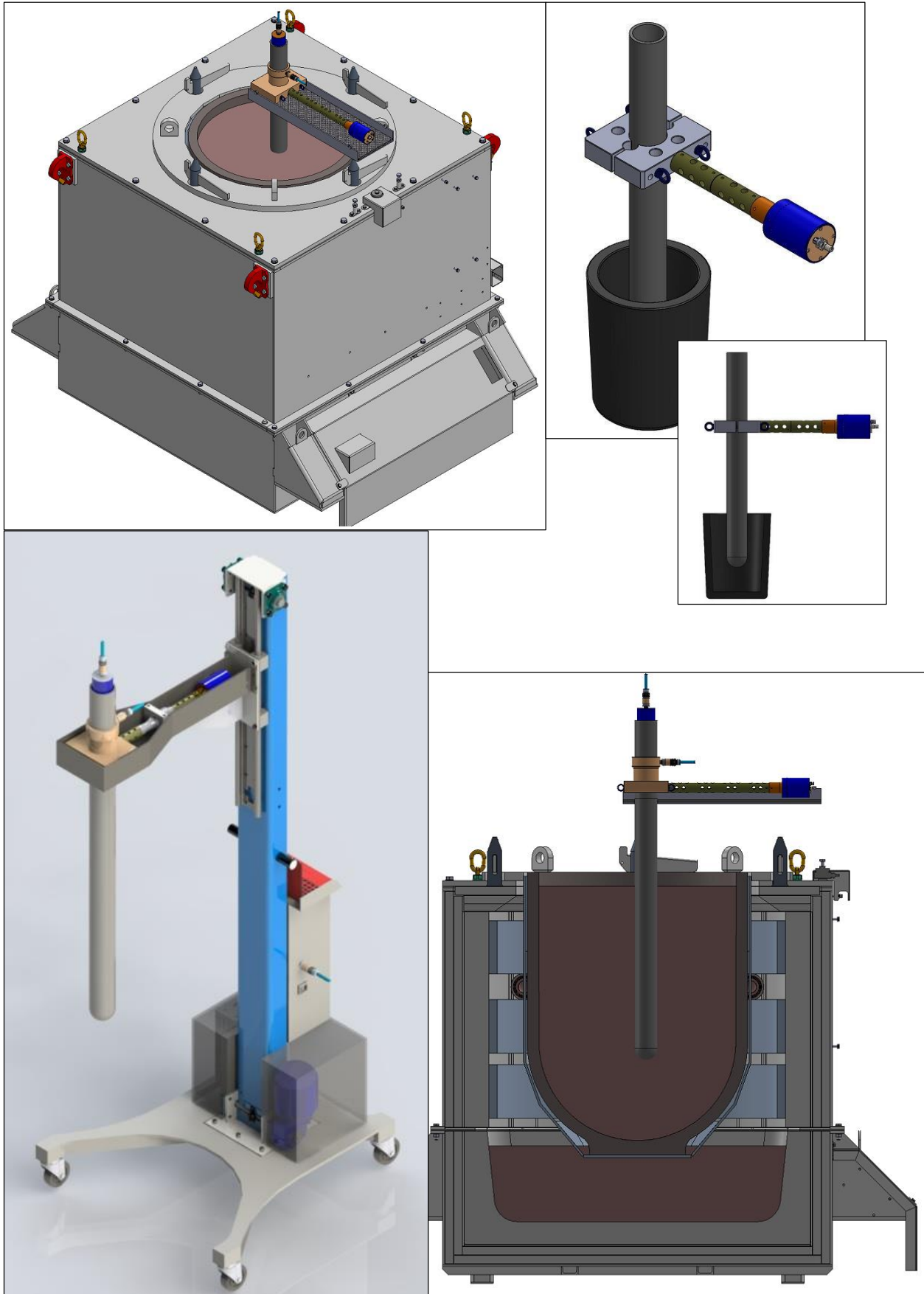
(2) In real metallurgical conditions, for every new, unknown, or previously still not ultrasonically and parametrically tested and characterized alloy, and in a specific production line we would need to determine optimal temperature for degassing, optimal temperature for grain refinement, and to find or decide about compromising and acceptable technological temperatures and processing time intervals, since every small change in metal composition is requesting new laboratory parametrization. Such parametric characterization should be made in a well-equipped technological and scientific laboratory (meaning not in the same place where aluminum will be casted). We always have to do proper preparation and testing in the lab first, and then apply ultrasonic processing in real production. Initial laboratory testing and characterization of each aluminum alloy is taking certain time and has certain price. We cannot make generally valid (or generally applicable) aluminum alloys characterizations, meaning that producer who is interested to test ultrasonic processing absolutely needs to present all relevant information about the alloy and technological conditions in his production. Mentioned, initial parametric, laboratory testing should be realized in the MPI laboratory (in Europe), using exactly the alloy samples that will later be treated in production. Clients who are well equipped

maybe already have good scientific laboratory for testing and this should be realized in collaboration with MPI experts, at least first time (meaning this preparatory phase has its price and its duration).

(3) Usually many new clients (not well informed and not scientifically supported) are immediately interested that we jump to a real metallurgical production, without analyzing casting-line conditions, in order to see results the next day, and this is not realistic and in 99% of cases not possible. We will need to analyze real production line of any aluminum factory where we intend to apply ultrasonic processing, to see all drawings and pictures of the casting line, or casting situation, analyze flow channels, crucibles etc. We need to get real 3D drawings of relevant production equipment, because MPI ultrasonic equipment should be conveniently customized to fit in a proper place, and casting line or crucible should also be conveniently adjusted or modified (to have necessary operating, holding and safety conditions for ultrasonic processing), and all of such preparatory activities have certain duration and certain price.

(4) The simplest (mostly educative and introductory) ultrasonically assisted casting situations are related to static laboratory testing in order to avoid complex preparatory steps. If somebody decide seriously to master ultrasonic metallurgy on a production level, he needs to do everything systematically and properly, without technical gambling. Any trial and error strategy should be avoided, because we already know what important and unavoidable steps to rich full success are (such as preliminary, parametric, laboratory diagnostic to find optimal temperatures and processing times for every new alloy or new technological conditions... and later we can safely apply ultrasonic processing). We do not have universally working and miraculous ultrasonic processing device, applicable to everything regarding liquid metals. Every time we need to formulate customized solution... For MPI, every new client, new technological line, new alloy and new testing presents several months of preparatory and design work (lot of time and big associated expenses). Client should also make lot of preparations in order to modify his casting equipment (presenting additional expenses).

5. Design options available for degassing of aluminum alloys in a crucible



6. General Considerations for CC and DC casting process

For ultrasonic grain refinement process, flow rate (m^3/h or l/min) and casting speed should be evaluated in order to establish the best operating conditions. Another very important aspect for the same process is the melt cooling rate. For instance, in DC casting is normal to have values between $0.5 - 2 \text{ K/s}$, contrary to what happens in CC casting where cooling rate can be $200-1000 \text{ K/s}$. These values show that in case of DC casting it will be possible to have degassing and refinement in a sump, but such treatment will depend on the product shape: (i) billet or (ii) ingot.

Normally billets have around 250mm of diameter (meaning that here is not possible to apply US directly in a sump). In cases of sufficiently big ingots, presenting a rectangular geometry, it is possible to apply US directly to sump.

In both cases: DC and CC casting, the most important is to reduce the hydrogen level by degassing. Regarding grain refinement, when we compare both processes, the situation is different, i.e., in case of CC casting the effect of high cooling rate and squeezing of twin rolls will destroy or promote longer grains. In DC casting can be easier to get good grains refinement. However in this process the grain refinement will depend on final product (remelting, rolling, etc.).

Check List / Reminder – CC Casting

- (1) CC casting is a process where is possible to achieve a low level of hydrogen, however grain refinement will present always the problem due to mechanical distortion promoted by the squeezing of twin rolls.
- (2) The ultrasonically resonating tube (degassing sonotrode) should be submersed **400 to 450 mm** in a liquid metal inside a launder.
- (3) The distance between ultrasonic ceramic tube and the twin rolls should not be more than **1m**.
- (4) We need to know which Al alloys processed in CC casting are.
- (5) Which is the temperature near twin rolls?
- (6) Is there a possibility to change or adjust operating melt temperature?
- (7) What kind of mechanical structure can be used to hang and support ultrasonic device? For instance, using flexible steel cables, or directly with a specifically designed holding and lifting

device. Mentioned lifting device can be programmed to perform vertical movement (up and down, periodical motion).

(9) It is important to have a supply of pressurized air for cooling ultrasonic device.

(9) We need single phase main supply, electric source 230 Vac.

(10) The trial tests should collect different parameters, such as: Temperatures in different positions, velocity of rolls, etc....

(11) After tests the samples should be characterized on microstructure and mechanical properties. Is there a possibility to make such analyses in client's labs?

(12) In CC casting applications we need to know what is more important for a client: Low porosity? Reduced grain size? Elimination of a central line of segregation?

Check List / Reminder – DC Casting

(1) We need to know which Al alloys processed in DC casting are.

(2) What is the shape of castings? Billet or ingot?

(3) Processing temperatures?

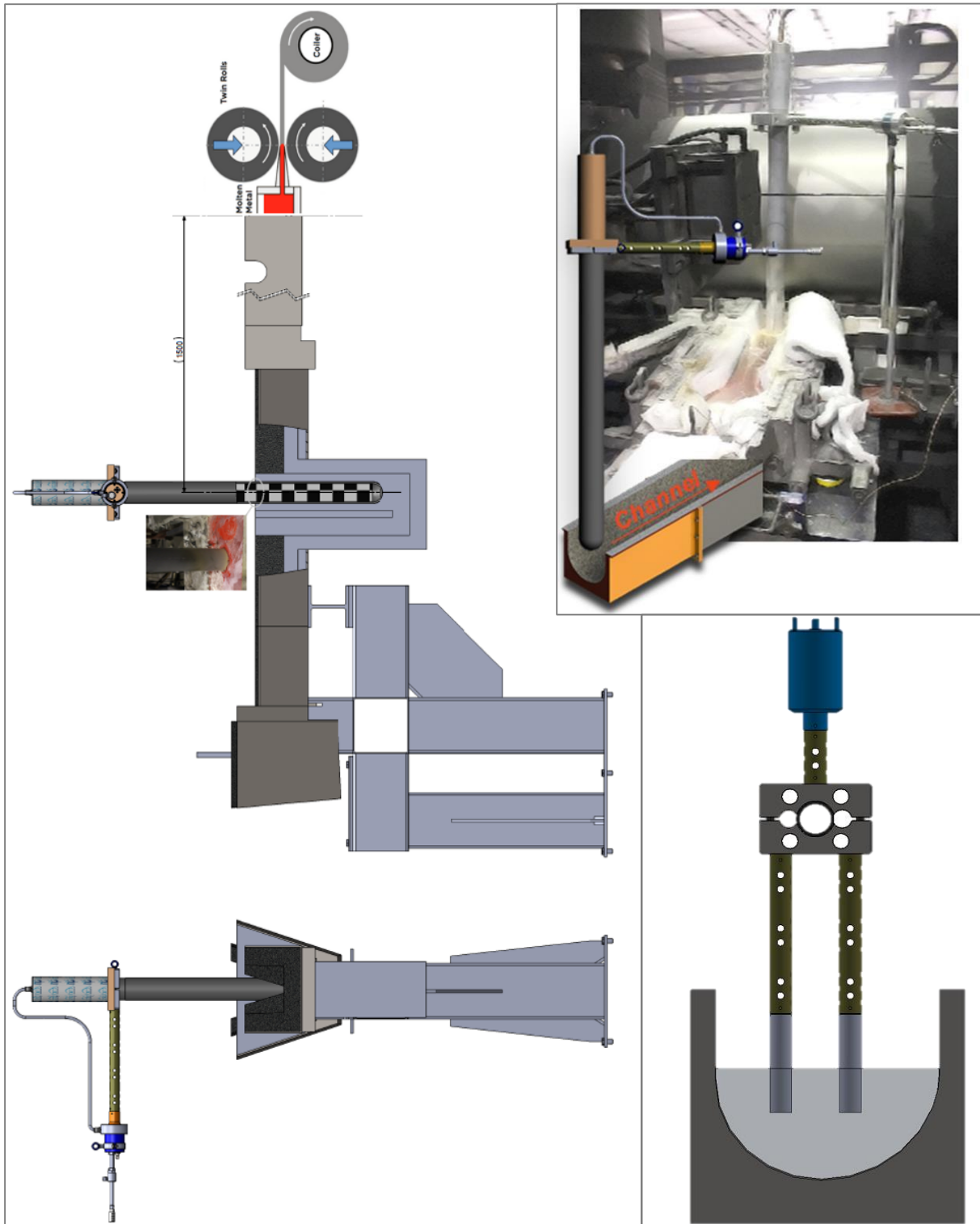
(4) What Client want in DC Casting? For instance: Degassing and refinement?

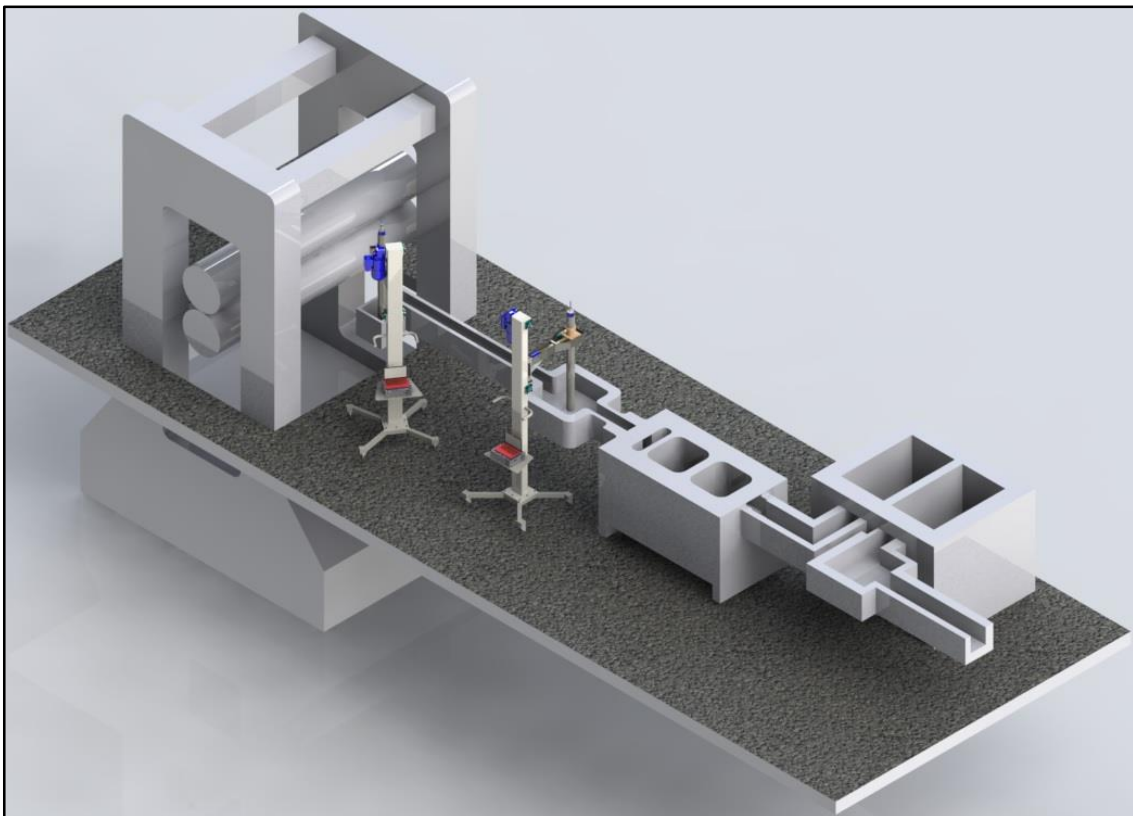
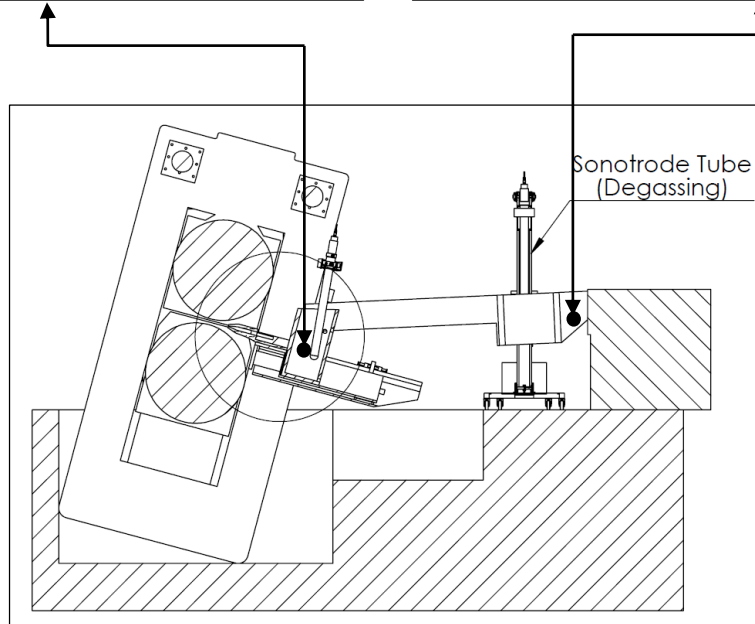
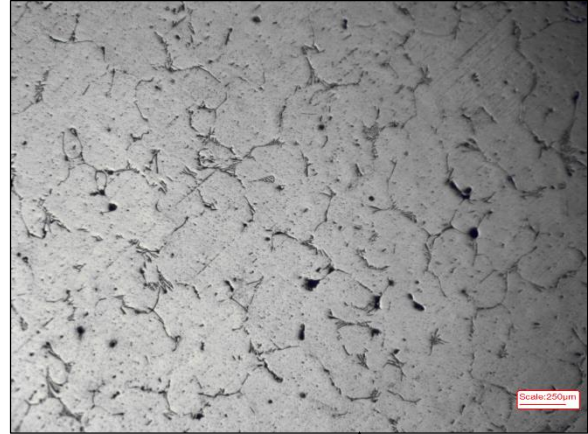
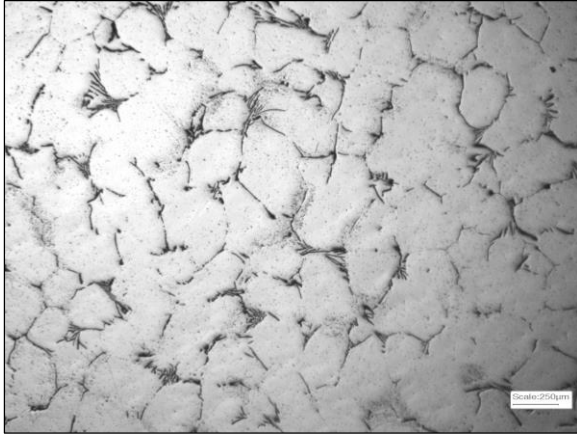
(5) “Macro segregation is one of major and irreversible defects in direct chill (DC) casting of aluminum alloys. Usually, the variation of the concentration of alloying elements throughout the cross section of the billet results in thermal and mechanical properties variation, which impair the quality of final products. The cause of macro segregation is the relative movement of segregated liquid and solid during solidification. Due to these driving forces, the extent of segregation in a real DC casting depends not only on the thermo-physical properties of the alloy but also on the actual casting parameters influencing the solidification process (e.g. casting speed, cooling rate and melt feeding).”

Has Client such questions or problems? Is Client interested to solve such problems? MPI device can improve significantly problematic of segregation. With correct operating parameters we can eliminate the effect of segregation promoting a more homogeneous microstructure.

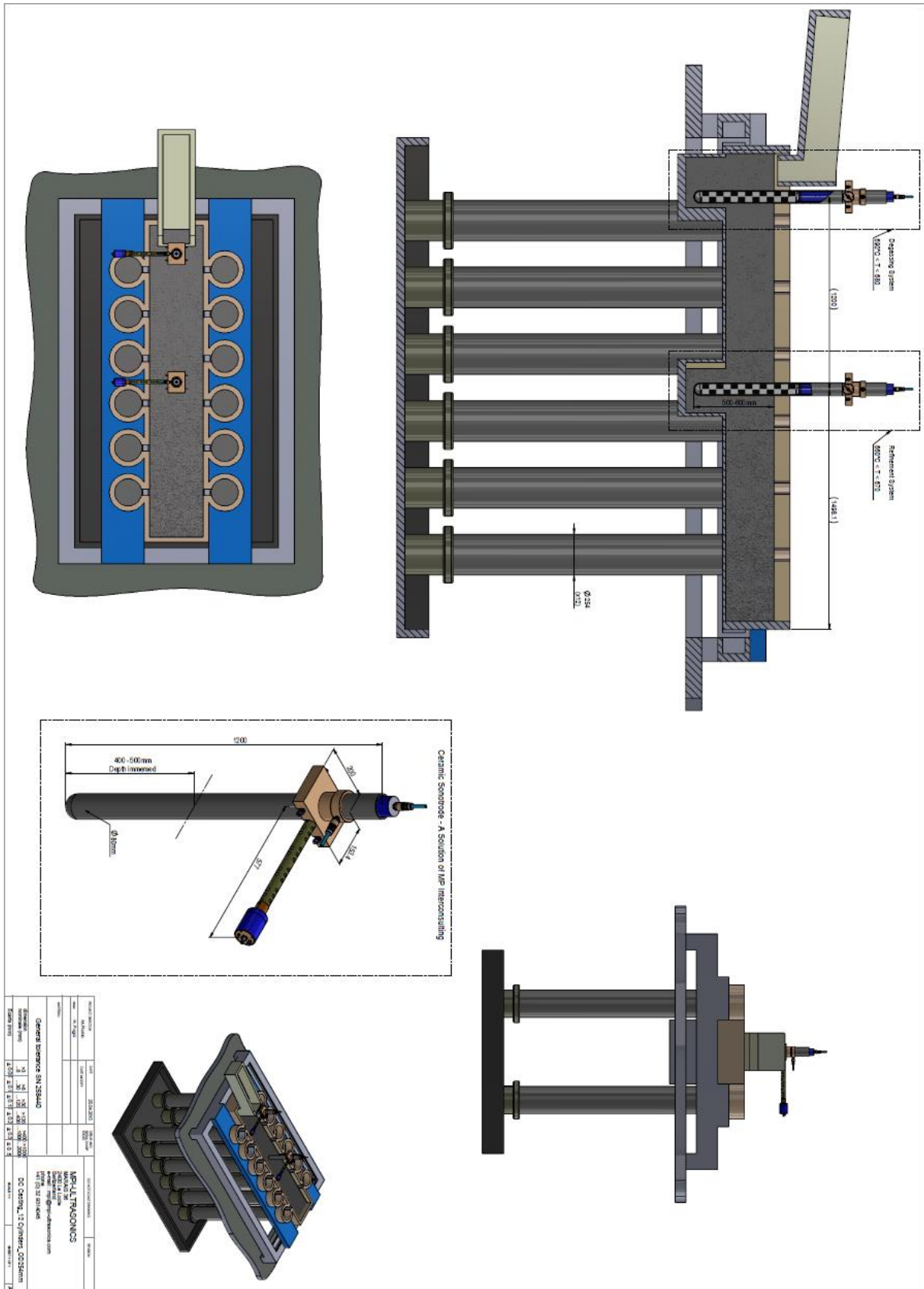
7. Design options available for CC Casting

Proposed layout should be adjusted to real dimensions of relevant casting equipment. Also there are situations convenient to introduce 2 of such US systems for degassing and refinement.



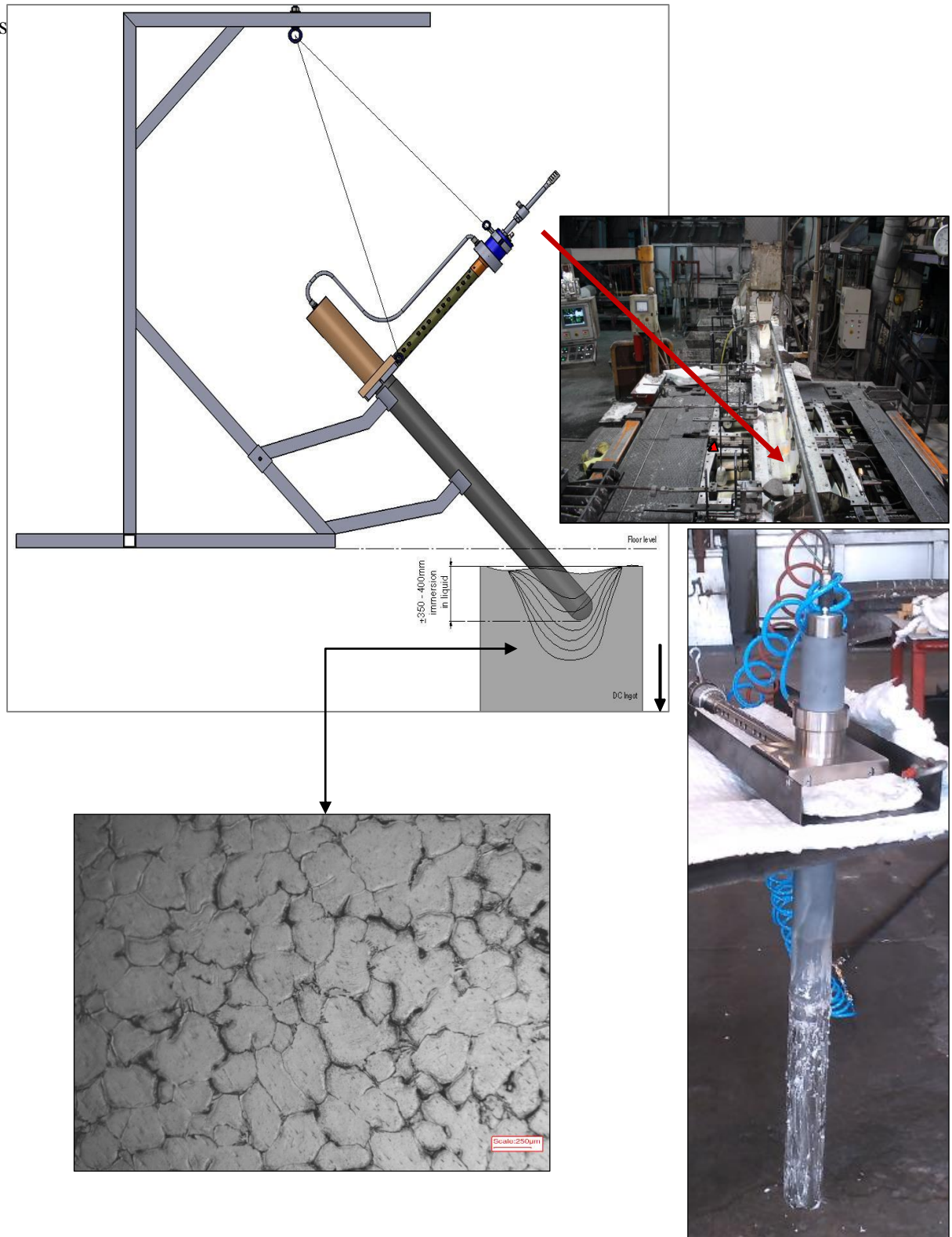


8. Design options available for DC Casting - For billets...



For ingots...

The figure below shows the ultrasonic device suitable to perform treatment of aluminum alloys in a sump of DC-cast ingot. The use of ultrasonic device based on the MMM technology will allow the formation of non-dendritic structure during DC casting making the ingot structure more homogeneous and decreasing the macro segregation. The layout proposed should be adjustable



9. Design options available for HPDC

