Design and realization of an experimental cold crucible levitation melting system for light alloys

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Thanks to their properties of ultra-lightness and high strength/weight ratio, Mg and Al alloys find increasing employ in aerospace, automotive and biomedical applications. These alloys can be formed using all the conventional technologies used for other materials, like casting and forming. However, the mechanical properties of the final components are significantly influenced by the quality of the starting liquid metal. In fact, the quality of the starting liquid metal has been substantially increased in recent years, thanks to the improvement of cleaning technologies. To this purpose, electromagnetic processing of materials has evolved as an important experimental technique in the fields of material processing, associated with applications such as shape controlling, flow driving, online detecting, controlled heat generation, inclusion removing, magnetic levitation. In particular, electromagnetic levitation, as a promising technique, can be helpful to create some new phenomena and discoveries, especially in melting process. This work describes the design, optimization and realization of a cold crucible levitation melting (CCLM) system for light alloys. Electromagnetic models are used and applied in FEM codes to numerical simulate the working range of the CCLM.

The simulation results show good agreement with experimental data.

Keywords: aluminium alloys, titanium alloys, magnesium alloys, solidification, melting and remelting, numerical simulation

INTRODUCTION

Melting and solidification of metals in cold crucible by magnetic confinement is an important subject of study and experimentation in a small number of laboratories in the world. The cold crucible operation is based on the use of a time-variable magnetic field that induces currents in the metal mass in process. The induced currents produce not only the metal heating, but also generate a repulsion force respect to the magnetic source. This force is used to lift up the metal mass in process by separating it from the crucible walls, and so obtaining the levitation and magnetic confinement of the molten metal. To achieve the conditions of solid and liquid state levitation is necessary to create a magnetic force F_{magn} equal and opposite to the gravity F_g [1]:

$$F_{magn} = F_g \qquad (1)$$

$$\int_s \frac{B^2}{2\mu} ds = \int_v \rho g dv \qquad (2)$$

where B is the magnetic field, μ the magnetic permeability, ρ the density, g the acceleration gravity, and s and v the surface and the volume of the specimen respectively.

The water-cooled metallic crucible is used to stabilize the molten metal by concentrating the magnetic field into a localised region and to provide a support for the material.

The main advantages achievable with this technique are the possibility to avoid the casting contamination with the material coming from the crucible [2,3] and to obtain alloys from extremely reactive materials or with different densities, by mixing up the casting produced by the induced currents and thermal gradients [4,5]. Other significant features of cold crucible levitation melting (CCLM) are as follows:

- Better temperature uniformity during metal casting and higher homogeneity in the nucleation of grains during the solidification process; these advantages are due to the convective motions in the molten metal, which are induced by a rotating magnetic field generated by the inductor. These motions allow to stir the liquid and therefore to homogenize the thermal field, i.e. without temperature gradients, and to obtain a completely equiaxed grain structure. Further, the convective motions favour the alloying additions [6,7].
- Accurate measurements of physical characteristics of materials [8].
- The formation of metastable phases and finer microstructures; this will improve the final mechanical properties of the components.
- High undercooling values are obtained as the liquid is completely surrounded by air and this allows to improve the heat exchange [9,10].

These peculiarities make the confinement technique in cold crucible particularly attractive for industrial applications, for example in the production of metal alloys for biomedical use and creep resistance alloys [5]. In general, the integrity and properties of the final components are strongly influenced by the liquid metal quality, which sometimes could be affected by a great number of solid impurities. Certainly, the most important advantage of the magnetic levitation casting process, eventually in controlled atmosphere or in vacuum camera,

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consists on the possibility to obtain a "clean" metal, that is not contaminated by impurities released from crucible walls, typically refractory. In addition, by using the magnetic levitation melting and solidification process, the eventual elaborating out furnace processes could be eliminated, i.e. a single melting process.

A typical casting production cycle offers various occasions to produce defects and inclusions. In the industrial field of light secondary alloys production, that is alloys obtained from scraps, slagging, degassing operations and filtering systems result to be mandatory [11,12]. In this last field, electromagnetic stirring systems have been recently employed to improve the final quality and productivity.

In the present work, an integrated approach to design and realize a levitation melting system for light alloys was developed. This study evolved through the analysis and characterization of an electric inductor with or without a cold crucible. Electromagnetic models were used and applied in FEM codes to numerical simulate and optimize the on-service behaviour of the CCLM apparatus.

THE DEVELOPMENT OF THE DTG APPARATUS

The development of a magnetic levitation melting apparatus was started at DTG with the specific purpose of building a flexible experimental device, suitable for exploring the possibilities opened by the levitation melting of light alloys under various conditions.

On the basis of the analysis of the bibliographical references available, a feasibility study of a full-levitation magnetic induction system, suitable for levitating, melting and solidifying a charge of about one hundred grams of light metal, was carried out.

Feasibility study of a full-levitation magnetic induction system

The device was initially intended to operate at a frequency of few kHz with an electrical power of about 10 kW. A (audio) power amplifier having a nominal power of 10 kW in the frequency range 20 Hz -10 kHz (rated voltage and current are 140 V rms and 70 A rms respectively) was chosen at the beginning to reduce the investment costs.

In order to assure minimal contact between the molten charge and other surrounding materials before solidification and also for easy practical operation of the device, two different options were considered:

a) full levitation melting without crucible
b) full levitation melting with cold crucible.

The option of the semi-levitation with cold crucible, which had already been used in several labs and industrial processes [13,14], was not considered.

The levitation without crucible is clearly more simple from the design and construction point of view, and is more energy efficient, but it has some practical and theoretical disadvantages, mainly due to the following reasons:

1) a thermally insulating protective enclosure is in any case necessary between the inductor turns and the molten metal, both during the process start-up and in case of loss of levitation of the molten metal;
2) the possibility of shaping the magnetic field and the corresponding magnetic pressure distribution on the molten metal is limited by practical constraints on size and bending radius of the inductor turns, and therefore it is not possible to assure a sufficient magnetic pressure in the lower part of the metal charge if the size of the charge is larger than few centimetres.

Figure 1 shows a numerical simulated example of the effects of a cold crucible on the magnetic field distribution. It can be observed how, in the presence of a conductive crucible, the magnetic field lines are concentrated towards the centre of the crucible, producing an increased magnetic pressure and levitation effect.

For the previous reasons, the initial concept of the apparatus included a copper crucible for the passive stabilization of the molten metal (similar to that of Fuji CCLM [5]), even if this solution intrinsically implies a reduction in the energy efficiency of the system due to the large power dissipated by eddy currents in the crucible.

For the initial feasibility study of the cold crucible system, a 2D simplified electromagnetic FEM (finite element method) model was set up using Maxwell® Student Version (by ANSOFT). The model assumed an overall axisymmetric geometry, with a cup-shaped copper crucible, surrounded by a multi-turn inductor and containing a charge of molten aluminium alloy inside.

The multi-turn inductor was considered as a set of "source" conductors with circular cross section and fixed current density. Both the aluminium charge and the copper crucible were modelled as "passive" conductors affected by eddy currents, the latter however subjected to the supplementary condition that the total current flowing in the azimuthal direction is zero, in order to account for the existence of at least one insulating segment in the crucible.

The shape of the crucible cup and its thickness, the number of turns and the operating frequency were considered somehow free design parameters for the design optimization. In the analyses, the shape of the molten charge was assumed to be fixed with respect to the crucible, in such a way as to assure a constant gap of about 4 mm. Figure 2 shows the geometry of the first crucible considered for the design optimization.

For every design, the CAD model was drawn and imported in the simulation software where a FE mesh for the inductor, the Al

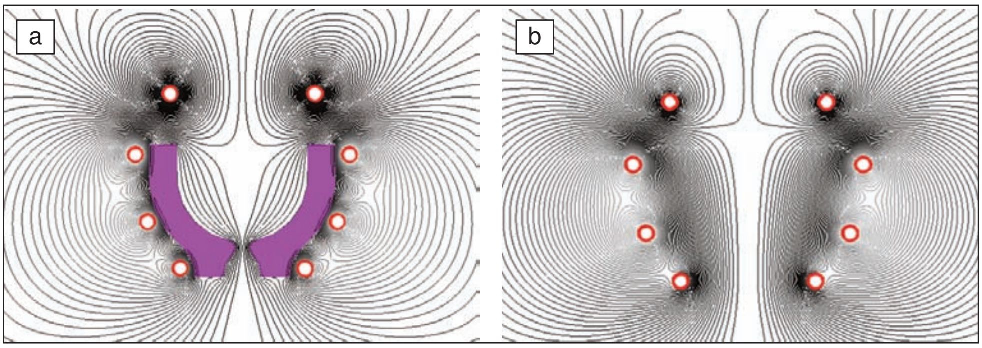


FIG. 1
Differences in the magnetic field distribution (a) with and (b) without a cold crucible; numerical simulation carried out with 4 turns, an alternate current of 800 A and a frequency of 24 kHz as boundary conditions.

Differenze nella distribuzione del campo magnetico (a) con e (b) senza crogiolo freddo; simulazioni numeriche condotte ipotizzando un induttore a 4 spire, una corrente alternate di 800 A e una frequenza applicata di 24 kHz.

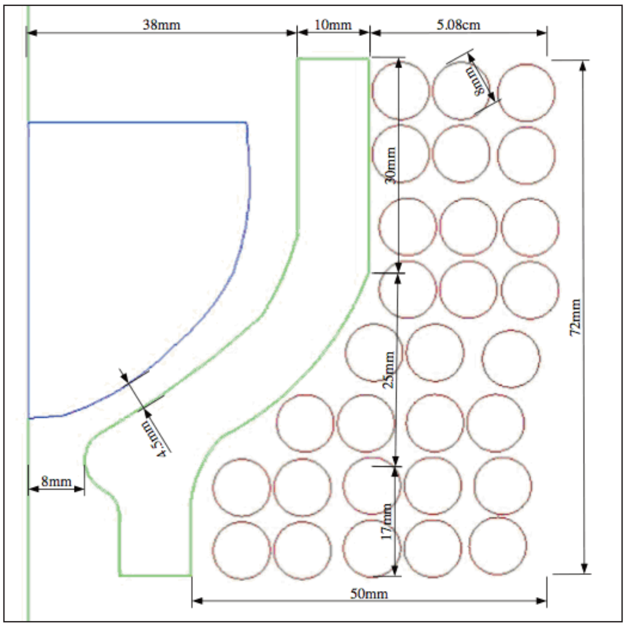


FIG. 2 ***Geometry of the inductor, crucible and molten metal charge considered in the design optimization. All components are considered axisymmetric.***

Geometrie dell'induttore, crogiolo e carica di materiale fuso considerati durante il processo di ottimizzazione. Tutti i componenti vengono considerati assialsimmetrici.

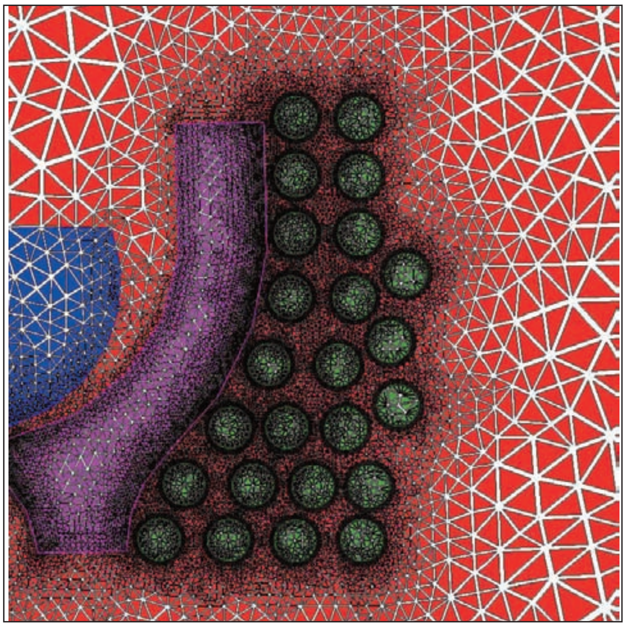


FIG. 3 ***Details of the mesh used for 2D numerical simulation with Maxwell® software.***

Dettagli della mesh utilizzata per le simulazioni numeriche 2D con l'ausilio del software Maxwell®.

specimen, the surrounding air, and eventually the cold crucible was generated. Being the mesh size a crucial parameter for the quality of the results and for the computation time, the meshing operation was always carried out under manual control. Figure 3 shows the mesh generated for 2D simulation with Maxwell® software. The initial conditions for numerical simulation were defined to reproduce eventually the further experimental parameters for an useful comparison.

The FEM model was set up assuming that the inductor is fed by a sinusoidal (AC) power supply with prescribed current and frequency and allowed the calculation of the induced current density J (A/m^2) in all the passive conductors and of the magnetic induction field (or flux density) B (Tesla) in the whole domain (passive conductors and surrounding air or vacuum). Both J and B are vector quantities (in space) having sinusoidal time evolution, with the same frequency as the inductor current and different phase in general. The resulting magnetic force distribution on the metallic charge was then calculated using the expression F=J×B, which gives the force density per unit volume (N/m^3) caused by the eddy currents in conductive materials. As both vectors J and B are sinusoidal in time, the force density F can be separated in two components: the first one (related to the component of J which is temporally in phase with B) results to be constant in time, the second one (related to the component of J which is temporally in quadrature with B) is sinusoidal with a frequency double of that of the current in the inductor. Being this frequency of the order of some kHz, only the first component produces a useful effect on the metallic charge, the second component can be disregarded, having a period much shorter than the timescale of the macroscopic movements of the molten metallic charge. Considering only the in-phase components of J and B and the Ampere law:

$$\nabla \times \left(\frac{\mathbf{B}}{\mu}\right) = \mathbf{J} \tag{3}$$

the constant (useful) component of the force density F can be written as:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} = \left(\nabla \times \frac{\mathbf{B}}{\mu}\right) \times \mathbf{B} \tag{4}$$

which can then be separated in two parts:

$$\mathbf{F} = \left(\nabla \times \frac{\mathbf{B}}{\mu}\right) \times \mathbf{B} = \left(\frac{1}{\mu}\mathbf{B} \bullet \nabla\right)\mathbf{B} + \nabla\left(\frac{1}{\mu}\mathbf{B} \bullet \mathbf{B}\right) = \frac{1}{\mu}\,(\mathbf{B} \bullet \nabla)\mathbf{B} + \nabla\left(\frac{1}{\mu}\left|\mathbf{B}^2\right|\right) \tag{5}$$

$$\mathbf{F}_{rot} = \frac{1}{\mu}\,(\mathbf{B} \bullet \nabla)\mathbf{B} \tag{6}$$

$$\mathbf{F}_{irrot} = \nabla\left(\frac{1}{\mu}\left|\mathbf{B}^2\right|\right) \tag{7}$$

The first part of the force density, F_{rot} is divergence-free and therefore can only produce internal rotation of the molten metal, i.e. stirring phenomena. The second part of the force density, F_{irrot} is the levitation force and can be expressed as the gradient of the magnetic pressure $1/\mu\ ]B^2]$. The resulting pressure distribution and the total force acting on the aluminium charge was then calculated by numerical integration. At the frequency considered, the stirring force is usually negligible with respect to the levitation force and the forces are concentrated on a thin external layer whose thickness is only about 1 or 2 mm, which is essentially the electromagnetic penetration depth of the material considered (see Figure 4).

By choosing a suitable shape for the inductor and for the cold crucible, the magnetic pressure distribution was then adjusted so as to match with good approximation the hydrostatic pressure produced by the weight of the molten metal charge.

However, given the axial symmetry of the device, it can be shown that the current density and the magnetic pressure are always null on the device axis. This fact indeed prevents from obtaining the pressure equilibrium at the bottom of the levitated charge, which is where the hydrostatic pressure due to the mol-

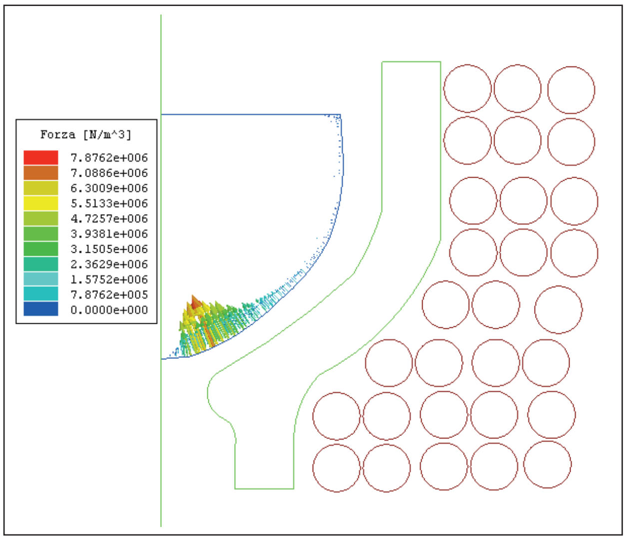


FIG. 4 ***Distribution of the force per unit volume obtained for the axisymmetric crucible shown in Figure 2 working at 3 kHz.***

Distribuzione della forza per unità di volume ottenuta per il crogiolo assialsimmetrico mostrato in Figura 2 e operante alla frequenza di 3 kHz.

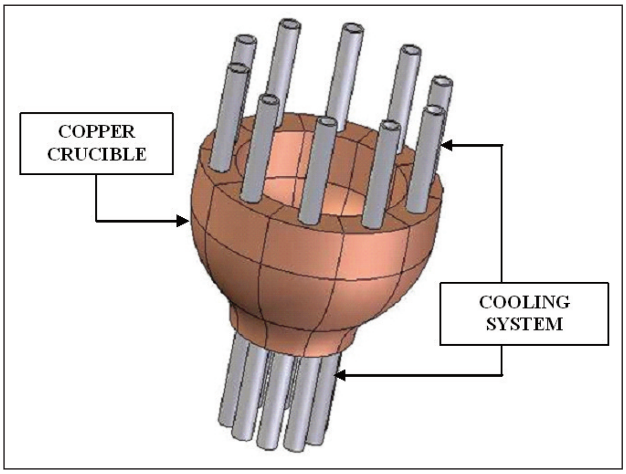


FIG. 5 ***The first cold crucible with the cooling system designed and developed in the present work.***

Primo crogiolo freddo con sistema di raffreddamento disegnato e sviluppato nel presente lavoro.

ten metal is highest. Fortunately, by appropriate shaping of the lower part of the crucible, it is possible to “compress” the magnetic field lines through the aperture at the bottom of the crucible and to increase the field gradient around this critical null point. As a result, if the volume where the pressure equilibrium in the molten metal charge is not assured becomes very small and the surface tension can be sufficient to avoid the loss of material. For this reason the full magnetic levitation remains practically possible only if the size of the molten charge is not too large.

The numerical simulations showed that an apparatus based on the available power supply could be capable of processing up to few hundred grams of metal, which was considered large enough to produce metal specimens sufficiently meaningful for metallurgical tests. The simulations also showed that a water cooling system was necessary for the inductor and for the segmented copper crucible.

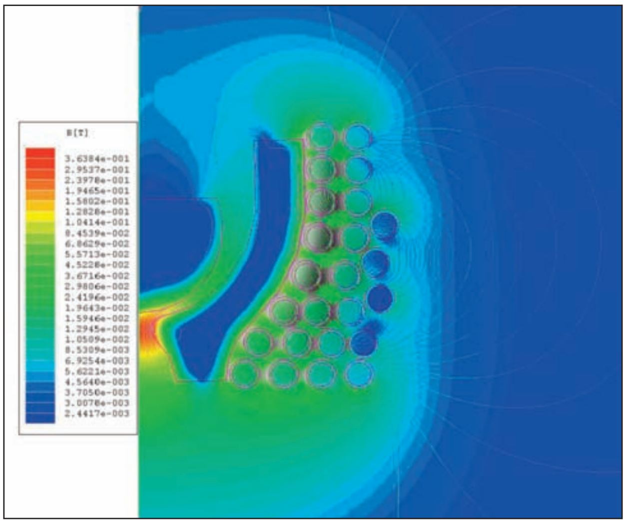


FIG. 6 ***Calculated magnetic field map in the CCLM configuration with 24 turns (axisymmetric model).***

Mappatura del campo magnetico calcolata nel caso di una configurazione del CCLM con 24 spire (modello assialsimmetrico).

EXPERIMENTAL RESULTS AND DISCUSSION

On the basis of this design, a first experimental cold crucible device was built and tested. A levitation melting system was developed for light alloys, such as Mg and Al alloys. The whole apparatus was designed with a melting capacity from 20 to 150 cm^3. The cold crucible was made by 10 copper section, insulated by kapton tape. Independent cooling channels were machined inside each section and water at room temperature was used as coolant. Figure 5 shows the first cold crucible system without the inductor. The inductor was made by a copper tube coil (=8 mm), tightly wound around of the crucible; the copper tube was surrounded by a thermoresistant insulating sheath and water-cooled too.

CCLM system with 24 turns

The first experimental CCLM system at DTG was provided with an inductor made of 24 turns. As shown in Figure 6, the maximum magnetic field is produced at the bottom of the crucible, in the region of the tapping hole. This configuration maximizes the forces acting on the charge to overcome the gravity because several magnetic field lines, which do not pass through the metallic walls of the crucible because of the eddy currents, are forced to pass through the tapping hole at the crucible bottom. The high intensity of the magnetic field near the tapping hole indicates a concentration of magnetic field lines and therefore a high magnetic pressure.

Figure 7 shows the distribution of the force vectors on the charge and on the cold crucible. The high intensity forces are not completely aligned with axis of the crucible and they are concentrated at the boundary of the tapping hole, producing low efficiency to counteract the gravity. As explained above, the magnetic force at the centre of the hole is locally zero. Therefore, this area is always a critical dropping point of the material in the liquid state.

The experiments, carried out at a resonance operating frequency of 2160 Hz, confirmed what indicated from the simulation analysis. At the solid state, the levitation is fine, the charge was sta-

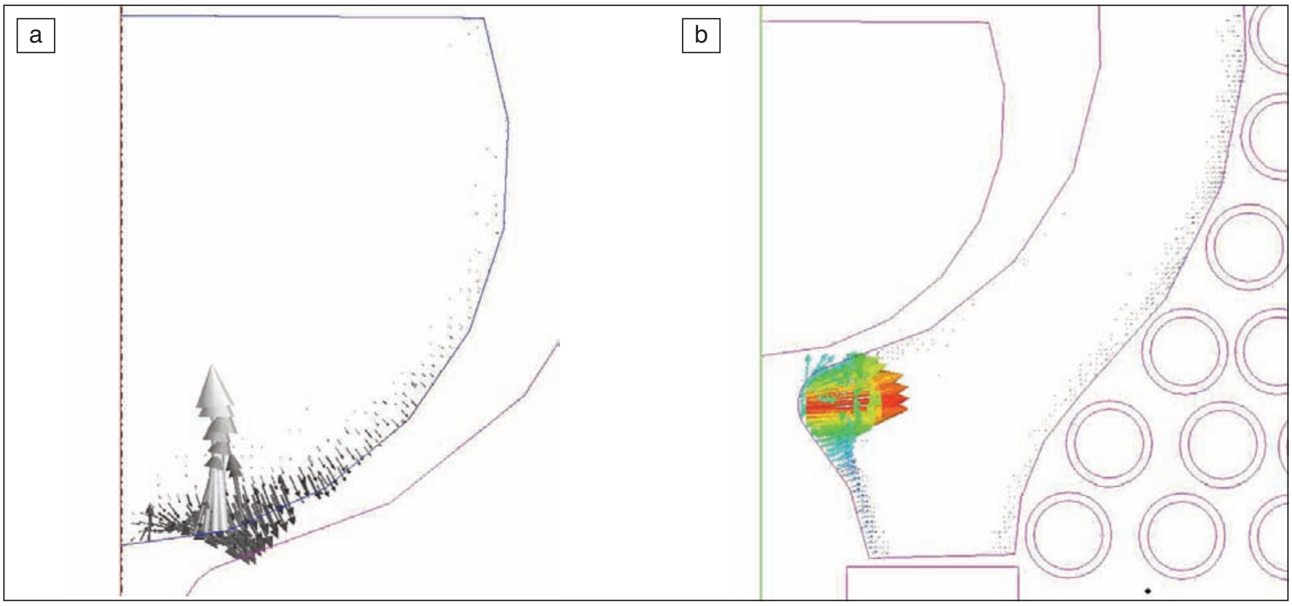


FIG. 7 ***Distribution of the force per unit volume on (a) the charge and on (b) the cold crucible in the CCLM configuration with 24 turns (axisymmetric model).***

Distribuzione della forza per unità di volume sul (a) materiale caricato e sul (b) crogiolo freddo nel caso di una configurazione del CCLM con 24 spire (modello assialsimmetrico).

ble only with small shifts and occasionally interacts with the wall of the crucible (Figure 8). Figure 7a shows the presence of small intensity forces directed to the walls of the crucible, while the highest force applied on the specimen, just below, produces sometimes the rotation of the specimen. When the specimen is completely melted, drops of molten metal started to flow through the tapping hole. This effect seemed to be related to the limited power available from the power supply. However, two problems were evidenced experimentally:

1. non axisymmetric effect due to crucible segments: the magnetic pressure on the molten metal was azimuthally not uniform and the molten mass assumed the shape of a flower, sometimes with a hole in the centre (see Figure 8). This effect was more evident when operating at low frequency (1-4 kHz), certainly because the larger penetration thickness allowed a larger magnetic flux to penetrate across the insulating sections of the crucible. This effect was also related to the relatively large "bowed" shape of the bottom part of the crucible;
2. limitation due to power supply overheating: the (air cooled) 10 kW power supply available could operate at nominal power only for few minutes at 1-6 kHz before overheating protection intervention. At higher frequency (7-10 kHz) the overheating was even faster and it was not possible to operate at nominal power for more than few seconds.

In order to increase the intensity of the forces applied on the specimen, a lower resonance operating frequency was produced by adding eight 21 μF-capacitors. The resonance frequency decreased from 2160 to 1610 Hz, the force increased from 5.12 to 6.13 N, but the melting time increased drastically.

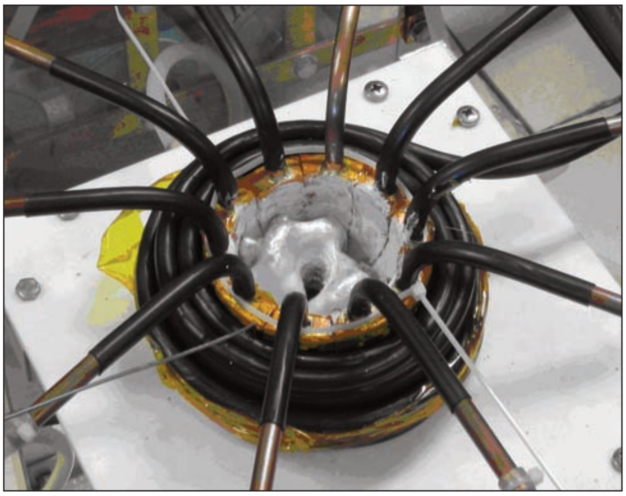


FIG. 8 ***Molten aluminium levitating inside the CCLM configuration with 24 turns.***

Alluminio fuso in levitazione all'interno del CCLM configurato con 24 spire.

CCLM system with 29 turns

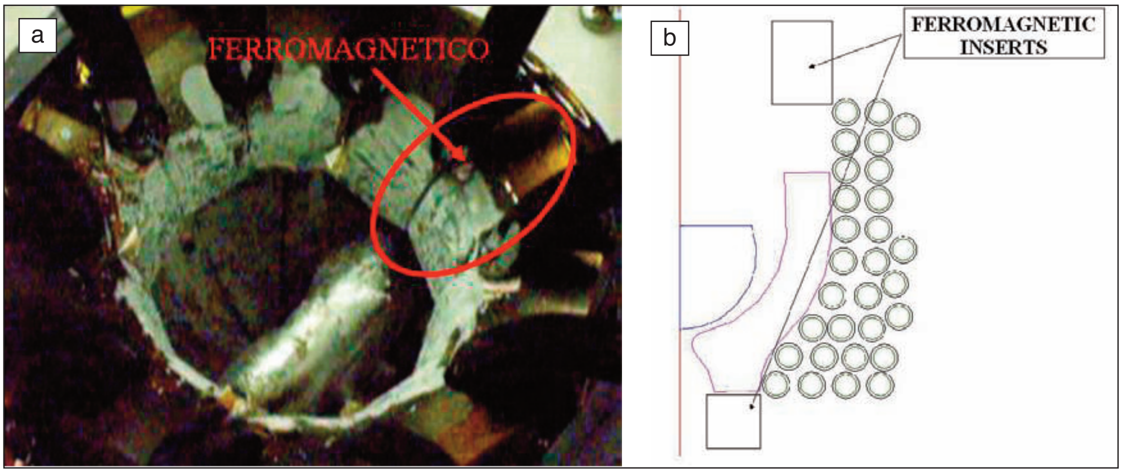
Increasing the number of the turns of the inductor the magnetic field distribution was similar to that shown in Figure 6. A comparison of the performances of the CCLM with 24 and 29 turns is shown in Table 1. It is observed how the maximum force increased about 20% with the same circulating current, thus im-

TAB. 1 ***Calculated performances of the CCLM apparatus with 24 and 29 turns respectively.***

Performance del CCLM con 24 e 29 spire rispettivamente.

Configuration (Turns no.)	Current (A)	Frequency (Hz)	Max Force (N)	Max B (mT)
24	536	1610	6.13	911
29	536	1400	7.42	967

FIG. 9 ***CCLM system with turns and ferromagnetic inserts; (a) detail of the location of ferromagnetic blocks at the top of the crucible and (b) CAD model used for numerical simulation.***



Sistema CCLM con spire e inserti ferromagnetici; (a) dettaglio dell'alloggiamento dei blocchi ferromagnetici sulla sommità del crogiolo e (b) modello CAD utilizzato per la simulazione numerica.

TAB. 2 ***Calculated performances of the CCLM apparatus with 29 turns and ferromagnetic inserts.***

Configuration (Turns no.)	Current (A)	Frequency (Hz)	Max Force (N)	Max B (mT)
29 + ferromagnetic inserts	536	1250	8.32	1023

Performance del CCLM con 29 spire e inserti elettromagnetici.

proving the levitation behaviour of the specimen. However, from the experimental observations, the time required for melting increased even more (~10 min); this is due to the reduction of the resonance operating frequency to 1400 Hz.

In order to optimize the shape of the new copper crucible and inductor, before starting the construction of a new prototype, several simulations and experimental tests in order to better understand the effect of the curvature ("bowed" shape) of the magnetic field lines facing the molten metal were carried out.

To this purpose, supplementary simulations and tests were carried out adding a ring constituted by ferromagnetic inserts aligned under the bottom of the old crucible and also some crucible-less configurations.

CCLM system with 29 turns and ferromagnetic inserts

Two ferromagnetic inserts were designed at the top and the bottom of the crucible. The ferromagnetic material used in the present work was a composite made by ferritic steel into a polymeric matrix, similar to a permanent magnet. The insert was constituted by 10 small ferromagnetic blocks were placed at the top of the crucible between the adjacent cooling tubes as shown in Figure 9a, while a ferromagnetic toroid with a square cross section of 18.5 mm surrounded the bottom of the crucible. The CAD model of the present design used for numerical simulation is shown in Figure 9b.

The numerical simulation results evidenced how the ferromagnetic inserts changed definitely the magnetic field distribution (Figure 10). The calculated performances shown in Table 2 indicate an increase of the levitation force (~8.3 N) and the maximum magnetic field (1023 mT), at constant circulating current. However, the resonance operating frequency still decreased leading to an increase of the melting time (~20 min).

The experimental observations confirmed the calculated results, moreover evidencing two regions of stable equilibrium of the Al specimen, that is where the levitation and the gravity forces are equal and opposite. One region was located at the level of the ferromagnetic circuit at the top of the crucible, while the other region stayed just behind the circuit. In these regions the charge is stable both at the solid and liquid state, but occasionally interacts with the containment walls.

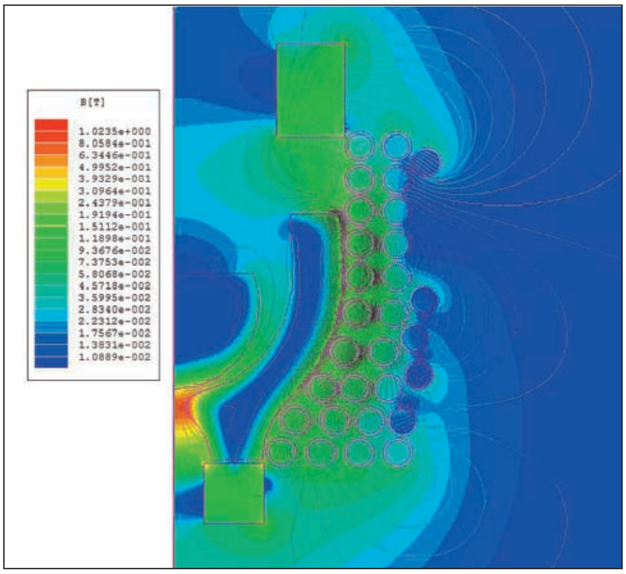


FIG. 10 ***Calculated magnetic field map in a CCLM configuration with 29 turns and ferromagnetic inserts at the top and the bottom of the crucible.***

Mappatura del campo magnetico calcolata nel caso di una configurazione del CCLM con 29 spire e inserti ferromagnetici posizionati sulla sommità e sul fondo del crogiolo.

Crucible-less configuration

Several crucible-less configurations were tested with different shape and "bowing" of the inner surface. These tests were very useful because they led to the conclusion that magnetic field

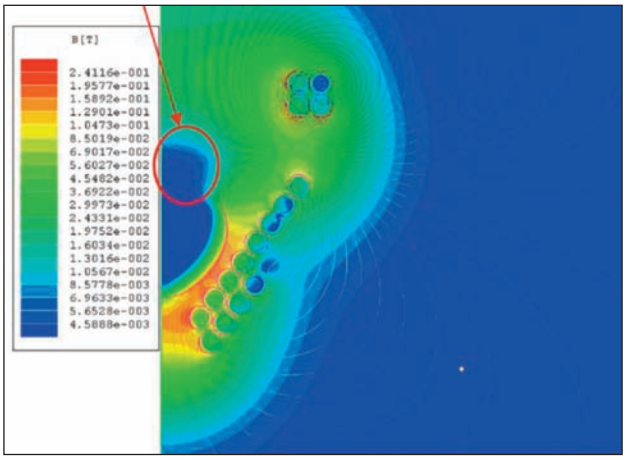


FIG. 11 ***Calculated magnetic field map of the crucible-less inductor used for the optimization tests of the levitation melting. Note the upper turns with reverse current, which produce a null-field region in the upper part of the molten metal indicated by the arrow.***

Distribuzione del campo magnetico calcolata per un induttore privo di crogiolo, utilizzato per ottimizzare la levitazione magnetica. Da notare le spire superiori con corrente inversa, le quali producono una regione a campo nullo nella parte superiore del metallo liquido, come indicato dalla freccia.

lines with straight "conical" shape and a slope of about 45 deg are the best in order to assure the compactness and the stability of the molten metal. Moreover, these tests showed the importance and effectiveness of the null-field region obtained by adding a number of reverse turns (Figure 11).

The experiments revealed how the most critical phase of the levitation melting process is the solid-liquid transition of the metallic charge as the stability of the system depends on the initial geometry of the charge. At this stage, an homogeneous heating of the material is necessary. Therefore, specimens with initial regular shape allows to stabilize the levitation behaviour both at the solid and liquid state (Figure 12); specimens with irregular shapes began to melt almost immediately from the bottom, while the top remained solid. This creates instability conditions of the charge because the solid part underwent a momentum produced by irrotational forces. The result is an excessive agitation of the molten metal, which immediately drops.

CCLM system with reverse upper turns

The design of the inductor with reverse turns placed at the top

FIG. 12 ***Levitating molten Al inside the experimental crucible-less system.***

Alluminio fuso in levitazione all'interno del sistema sperimentale privo di crogiolo.

of the cold crucible was adopted. The current circulating in these turns was reverse to that in the coil wound around the crucible. In order to obtain this configuration, the turns around the crucible were extended over the crucible but rolled in the opposite direction. The effect of the reverse circulating current in these turns on the magnetic field distribution was analysed by means of numerical simulation and shown in Figure 13. When the current circulates in the coils with the same direction (Figure 13b), the magnetic field lines are parallel to the main axis of the apparatus, i.e. the axis passes through the tapping hole. This results in a lower levitation effect on the specimen. Contrary in the case the current circulates with opposite direction in the coil placed at the top of the crucible; the charge is stabilize by the upper region where the magnetic field is null.

Figure 14 shows the comparison of the calculated and experimental magnetic field distribution (measured at reduced current levels in order to avoid damages to the magnetic field probe). As in the previous crucible-less configuration, two different regions can be observed:

- one in the upper part of the molten metal where a magnetic null-field there exists, due to the effect of the reverse turns;

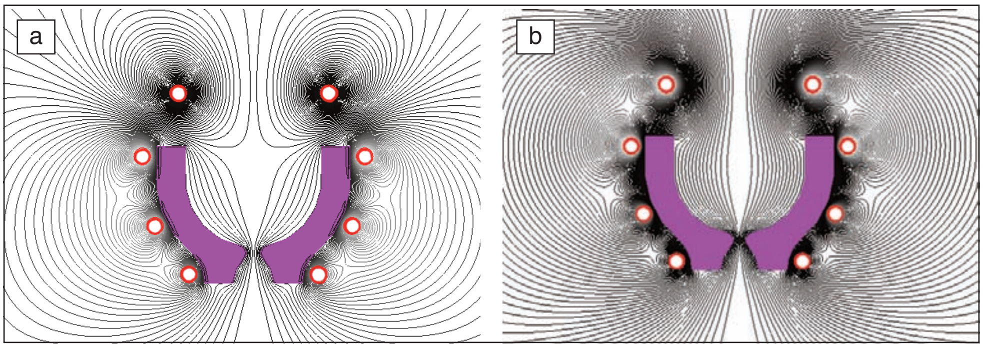


FIG. 13
Differences in the magnetic field distribution in CCLM system (a) with or (b) without reverse upper turns; numerical simulation carried out with an alternate current of 800 A and a frequency of 24 kHz.

Differenze nella distribuzione del campo magnetico nel sistema CCLM (a) con o (b) senza spire inverse nella parte superiore; la simulazione numerica è stata condotta imponendo una corrente alternata di 800 A e una frequenza di 24 kHz.

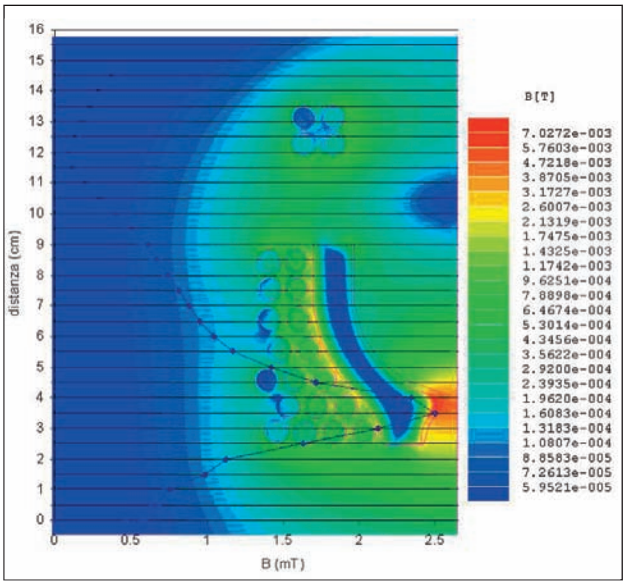


FIG. 14 ***Comparison of the calculated and experimental magnetic field distribution in the CCLM system with reverse upper turns (a reduced current value was used in order to avoid damages to the magnetic field probe).***

Confronto tra la distribuzione del campo magnetico sperimentale e numerica del sistema CCLM con spire inverse nella parte superiore (è stato utilizzato un valore di corrente più basso al fine di non danneggiare la sonda per la misura del campo magnetico).

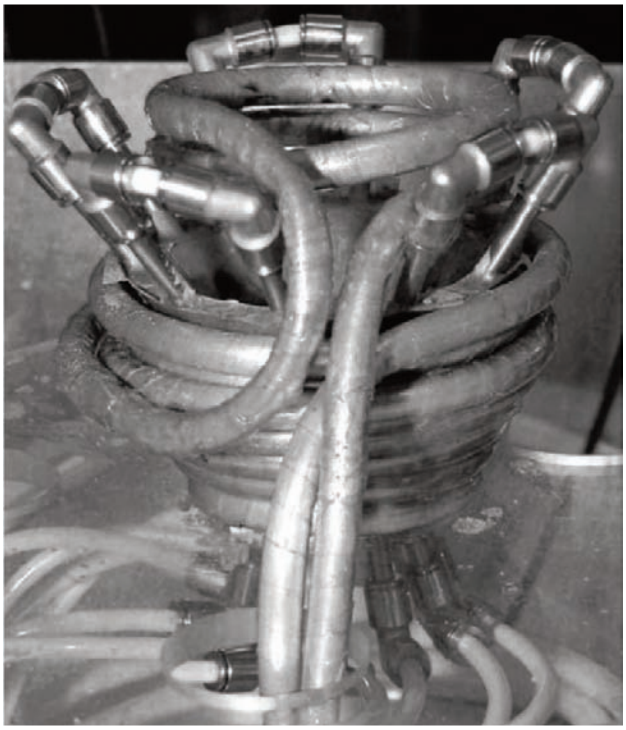


FIG. 15 ***Optimised inductor and cold crucible for light alloys melting.***

Induttore e crogiolo freddo, dopo la fase di ottimizzazione, per la fusione di leghe leggere.

- one close to the tapping hole where the magnetic field shows the highest values.

CONCLUSIONS

In the present work, an integrated approach to design and realize a levitation melting system for light alloys has been developed. The study characterizes a levitation melting system with or without a cold crucible. Electromagnetic models have been used and applied in FEM codes to numerical simulate the on-service behaviour of the CCLM apparatus.

On the basis of all the tests, a new crucible and a new inductor has been built, which incorporate all the experience gained in the previous tests and simulations (Figure 15). The tests with the new cold crucible levitation system are in progress. The system demonstrates much better performances, stability and flexibility with respect to the previous ones.

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REFERENCES

1) B.O. CIOCIRLAN, D.G. BEALE and R.A. OVERFELT, J. Sound Vib. 242, (2001), p.559.
2) G. BROIHANNE and J. BANNISTER, JOM 52 , (2000), p.21.
3) Q. WANG, CHUN-JIANG WANG, T. LIU, K. WANG and JI-CHENG HE, J. Mater. Sci. 42, (2007), p.10000.
4) C. TOSHINORI, S. MANABU, H. AKIRA, A. KATSUNORI, N. TAKUYA and M. TAKEO, J. Nucl. Mater. 307-311, (2002), p.555.
5) A. MORITA, H. FUKUI, H. TADANO, S. HAYASHI, J. HASEGAWA and M. NIINOMI, Mater. Sci. Eng. A 280, (2000), p.208.
6) O. FILIP, R. HERMANN, G. GERBETH, J. PRIEDE, V. SHATROV, A. GUETH and L. SCHULTZ, J. Magn. Magn. Mater. 272-276, (2004), p.e1857.
7) E. BAAKE, B. NACKE, A. UMBRASHKO and A. JAKOVICS, COMPEL Int. J. Comput. Math. Electr. Electron. Eng. 22, (2003), p.39.
8) A.K. GANGOPADHYAY, G.W. LEE, K.F. KELTON, J.R. ROGERS, A.I. GOLDMAN, D.S. ROBINSON, T.J. RATHZ and R.W. HYERS, Rev. Sci. Instrum. 76, (2005), p.73901-1-6.
9) P. GILLON, Method for melting and solidifying without contact an electric conductor sample, Patent. No. PCT/FR2000/002728, (2001).
10) D.M. HERLACH, J. GAO, D. HOLLAND-MORITZ and T. VOLKMANN, Mater. Sci. Eng. A 375-377, (2004), p.9.
11) J.E. GRUZLESKI and B.M. CLOSSET, The treatment of liquid Aluminum-Silicon alloys, American Foundrymen's society Inc., IL (1990).
12) G. TIMELLI, F. BONOLLO, Int. J. Cast Met. Res. 20, (2007), p. 304.
13) A. UMBRASHKO, E. BAAKE, B. NACKE and A. JAKOVICS, COMPEL - Int. J. Comput. Math. Electr. Electron. Eng. 24, (2005) p.314.
14) R. RAYMOND J. and K. GRAHAM, Cold crucible induction furnace with eddy current damping, Patent. No. PCT/WO2005/072207, (2005).

Abstract

Design e realizzazione di un sistema fusorio sperimentale con crogiolo freddo a levitazione magnetica per leghe leggere

Parole chiave: alluminio e leghe, titanio e leghe, magnesio e leghe, solidificazione, fusione e rifusione, simulazione numerica

La fusione e la solidificazione dei metalli attraverso un confinamento magnetico all'interno di un crogiolo freddo costituisce una tematica di studio e di sperimentazione in pochi laboratori nel mondo. Il funzionamento del crogiolo freddo (CCLM) si basa sull'utilizzo di un campo magnetico variabile nel tempo che induce delle correnti nel materiale metallico caricato. Le correnti indotte producono non solo il riscaldamento del materiale, ma anche generano una forza repulsiva rispetto alla sorgente magnetica. Questa forza viene utilizzata per sollevare la massa metallica staccandola dalle pareti del crogiolo, ottenendo in questo modo la levitazione e il confinamento magnetico del metallo fuso. I principali vantaggi ottenibili con questa tecnica sono, ad esempio, la possibilità di evitare la contaminazione del metallo con materiale proveniente dal crogiolo e di ottenere leghe partendo da materiali estremamente reattivi o con diversa densità, rimescolando il tutto attraverso le correnti indotte e i gradienti termici sviluppati.

In questo lavoro, partendo dalla bibliografia disponibile, è stato inizialmente condotto uno studio di fattibilità di un sistema a induzione a completa levitazione magnetica; tale attrezzatura avrebbe dovuto essere in grado non solo di portare a fusione una carica metallica costituita da una lega leggera (Al, Mg, Ti, ecc.), ma anche di mantenerla in sospensione sia durante la fase di fusione che di solidificazione. L'analisi preliminare di fattibilità condotta con l'ausilio di strumenti di simulazione numerica ha evidenziato gli effetti di un crogiolo freddo sulla distribuzione del campo magnetico. Si è osservato come, in presenza di un crogiolo conduttivo, le linee di campo magnetico sono concentrate verso il centro del crogiolo stesso, producendo un aumento della pressione magnetica e dell'effetto levitante (Figura 1). Il dispositivo così progettato era in grado di elaborare fino a poche centinaia di grammi di metallo, quantitativo considerato comunque sufficiente per produrre campioni per successive caratterizzazioni metallurgiche. Le simulazioni numeriche hanno altresì dimostrato la necessità di prevedere un sistema di raffreddamento per l'induttore e per i segmenti in rame costituenti il crogiolo (Figura 4).

Sulla base di queste risultati, è stato costruito e testato un primo dispositivo sperimentale (Figura 5). Il numero di spire dell'induttore così come l'utilizzo di inserti ferromagnetici o spire inverse, posizionate sopra il CCLM, è stato poi ottimizzato al fine di cambiare la distribuzione del campo magnetico con evidenti miglioramenti sui tempi di fusione del materiale e sulla levitazione magnetica dello stesso (Figure 6-14). L'attuale sistema fusorio con crogiolo freddo a levitazione magnetica sviluppato e ottimizzato presso il Dipartimento di Tecnica e Gestione dei Sistemi Industriali - DTG dell'Università di Padova presenta migliori performance, stabilità e flessibilità rispetto alle versioni precedenti (Figura 15).