Abstract

In the last decade, low-frequency electromagnetic casting has become an important industrial process for the manufacture of materials with enhanced mechanical properties. Basic physical laws are applied to describe the electromagnetic and temperature fields as well as liquid motion in the system. The choice of optimal technological parameters that control the final results of the process is discussed. Material’s microstructure formation is described and related to the physical fields’ properties. Lastly, mechanical properties are related to microstructure. The theory is supported by some experimental evidence.
1 Introduction

Many materials used in our daily lives and in industry go through a liquid phase during their formation or production. Casting of materials is used to transform a liquid into a solid (semi)product, that can be further processed and formed into a final product [1].

Many casting types exist, but low-frequency electromagnetic casting (LFEC) process will be the topic of this paper. Also, many general remarks described in the text have wide applicability to many casting varieties and materials being made.

LFEC is simple and efficient, and it has received a lot of industry’s attention in the recent decade due to its great potential [2].

The first (introductory) section of this text describes the importance of casting technologies and briefly describes both the conventional casting process and LFEC. An example of materials widely produced by LFEC is also given. The second section deals with the physical description of fields that are present in the system. It gives equations upon which the fields are based and discusses the importance of several technological (operative) parameters. The third section describes how a liquid transforms to a solid and what is the material structure like on a micro scale and how LFEC influences the microstructures of cast materials compared to those cast by a conventional casting technique. The last section shows some experimental proofs of the results of LFEC processes.

1.1 Importance of Casting Technology

Naturally occuring materials can not always be used for the production of products of high quality. They have to be refined and unwanted chemical compounds have to be removed. Therefore such a material has to be melt, the structure refined in some way and alloying elements can also be added. The next step is to solidify the liquid and reshape it into something useful. Casting is a manufacturing process by which a liquid material is usually poured into a mould, which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process.

Many types and variations of casting are known. Among the first in history was the casting of components. However, not only components are produced by casting, also raw materials in standardized forms (such as billets, blooms and slabs) can be made using this process.

These forms were first produced by the aid of ingot casting, and, from the middle of the twentieth century onwards, also by the aid of continuous and semicontinuous casting. In ingot casting, the melt is poured into one or several moulds where it is left to solidify. The method of ingot casting has its limitations. For example, it is impossible to increase the production capacity beyond a certain limit. If the amount of melt in an ingot is increased, the cooling rate will decrease, which leads to poorer material properties and difficulties in handling the final, bigger ingots. For this reason methods of continuous (and semicontinuous) casting have been developed. They consist of drawing out a strand of solid metal from the chill-mould while it is continuously fed with new melt from above. In semicontinuous casting the length of the strand is limited.

The following chapters are principally devoted to continuous and semicontinuous casting of billets.

1.2 Schematics of DC and LFEC processes

In a typical (semi)continuous casting process, liquid material comes from a furnace and flows down from a ladle into a tundish and is continuously melt from there into a vertical water-cooled chill-mould while a solid shell of the cast material, which contains melt in its center, is simulataneously extracted from the bottom of the chill-mould. The mould has to be an exellent thermal conductor.
in order to extract heat rapidly from the melt. During the passage of the material through the mould, a solid shell must be formed that is stable enough to keep its shape unchanged while it is continuously extracted vertically from the mould. When the material shell leaves the chill-mould it enters a series of cooling zones. The cooling medium is water, which is sprayed directly on the entire periphery of the casting. The principle of semicontinuous casting is demonstrated in Figure 1 (it applies well to continuous casting also). This is the conventional casting process, often called direct-chill casting (abbreviated and used in the text as DC).

Figure 1: A schematic of a conventional vertical direct-chill (DC) casting method on the left. A variation of a DC process, a hot top mould casting process, is depicted on the right. For details see [3].

In LFEC, the mould is surrounded by a coil powered by an alternating current. The current induces an electromagnetic field in the system. Figure 2 shows schematics of the LFEC and DC processes. As will be seen, the presence of an electromagnetic field significantly alters the process.

Figure 2: A cross-section schematic of the LFEC (left) and DC (right) processes. See [4] for details.

Material’s microstructure cast by a DC process results in many flaws (more on this in the third section) and further thermal homogenization treatment of the aluminum alloys represents a fundamental step in achieving the desired properties, but such a procedure implies a significant expense of time and energy. LFEC can significantly improve the cast structure and reduce costs and time needed to prepare the material.
1.3 Super-high Strength Aluminum Alloys

The most common materials to cast are steel, iron-based alloys, copper and aluminum. LFEC improves mechanical qualities of cast materials, therefore the process applies best to materials of wide use in aerospace and automobile industries. The aerospace industry demands the production of materials of low density, high strength and good hot work ability, high toughness, high corrosion resistance, ability to withstand high temperature and pressure differences and long-term reliability - to summarize, these materials have to perform well when others fail. Some examples of aerospace materials are nickel-based superalloys (for use in turbine blades of jet engines), titanium, steel and aluminum. The latter is due to its low density and good characteristics obtainable from alloying it with other elements also important in the automobile industry.

General characteristics of a LFEC process described in the following sections adapt to the production of all materials. However, in this paper the focus will be on the evaluation of the results of LFEC on aluminum alloys primarily, due to their wide use. Some experimental results that are shown, were gained after LFEC manufacturing of super-high strength aluminum alloys. According to the IADS (International Aluminum Designation System) these are alloys of the 7000 series (for example 7050, 7075). (According to IADS each alloy is given a four-digit number, where the first digit indicates the principal alloying element; series 7000 is a family of aluminum alloys with zinc being the principal alloying element.)

2 Description of Physical Fields in the LFEC Process

This section through equations and figures describes the fields that are established in the system, that consists of the melt, the mould, and the solidified material, and their characteristics.

The first subsection outlines the equations that describe the behaviour of the electromagnetic fields, the second subsection describes the heat flow through the system and out of it, the third subsection deals with melt motion and the last subsection shows the coupling of all phenomena and stresses the importance of numerical modeling of the processes.

2.1 The Electromagnetic Field

Under the effect of the periodic current, the inductor generates a variable magnetic field in the melt, which, in turn, gives rise to an induced current, so the melt is subject to electromagnetic body force caused by the interaction of the eddy currents $\vec{j}$ and the magnetic field $\vec{B}$. Another characteristic of the electromagnetic field in this geometry is a pronounced inclination of the magnetic field lines toward the axis of symmetry of the casting. A sample field for a simple model (where only the electromagnetic problem equations are solved) is shown in figure 3.

In LFEC, electromagnetic field can be described by the quasistatic form of Maxwell’s equations (without considering the displacement current):

\begin{align*}
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t}; \\
\nabla \times \vec{H} &= \vec{j}; \\
\n\nabla \cdot \vec{B} &= 0.
\end{align*}

$\vec{E}$ is the electric field intensity, $\vec{B}$ magnetic field density, $\vec{H}$ magnetic field intensity, $\vec{j}$ total current density. The mentioned equations are supplemented by $\vec{H} = \frac{\vec{B}}{\mu}$ and $\vec{j} = \sigma \vec{E}$, where $\mu$ is magnetic permeability and $\sigma$ electric conductivity. The Lorentz force density vector for a conductive material is given by:

\begin{equation}
\vec{f} = \vec{j} \times \vec{B}.
\end{equation}
Figure 3: Contour plot and vector field of a magnetic field for a simplified LFEC model, depicted from the model center to the outer edge of the coil. It should be noted that a solution of the field of this type is the solution of the electromagnetic equations only. The geometry of the model (blue lines), including the solidification layer (represented by a straight tilted line), are in this case the problem input. However, the solidification layer is in fact a part of the solution.

Using some of the vector calculus identities, the last equation can be rewritten as:

\[
\vec{f} = \frac{1}{\mu} (\vec{B} \cdot \nabla) \vec{B} - \frac{1}{2\mu} \nabla \vec{B}^2. \tag{5}
\]

The form of equation 5 is convenient because each component has, bearing the geometry of the process in mind, a distinct and predictable direction.

The first Lorentz force density component is a gradient of the magnetic field density vector in the direction of this vector, multiplied by the vector’s magnitude. It was assumed that the magnetic field lines are inclined toward the axis of symmetry of the casting. This means that the \( B_r \) component of the magnetic field density vector (in the cylindrical coordinate system) is small in comparison with the vertical \( B_z \) component. Therefore, the first Lorentz force density component in equation 5 is a rotational component (i.e. it is mainly vertical) and it will result in the enhanced transportation of heat and mass between upper and lower portions of the melt.

The second term on the right in equation 5 is approximately horizontal in the given geometry and pointed towards the symmetry axis when the frequency is sufficiently large. This part is a potential component (gradient of the square of magnetic field density) and it results in the decrease of the primary cooling intensity and the friction between billet and mould.

Coupled with the melt motion equations, the result of Lorentz forces is forced convection. Melt, poured from the inlet region is carried directly to the periphery and from there along the solidification front downwards to the central region. In the central region the melt flows upward and a meniscus is formed. Also, the contact zone between the melt and the mould is reduced (see Fig. 2), which reduces primary cooling intensity and results in better surface compared to an as-cast billet formed in DC casting.

There are two technological (operative) parameters that are easily adjustable during the casting process and have a profound effect on the electromagnetic field: frequency \( f \) and electric current peak intensity \( I \).

In general, with an increase in coil current peak intensity, the stirring effect of electromagnetic body forces and forced convection are intensified and all the effects are enhanced.

Optimal frequency determination is more difficult. As a principal parameter, frequency greatly influences the distribution of magnetic flux density in conductive media. In the process of electromagnetic casting, flow pattern and temperature field of the melt can be modified by means of frequency modulation, and optimized conditions of solidification can be obtained. The characteristic length, which specifies how the magnitude of magnetic field decreases as a function of
distance into the melt is the skin depth:

\[ \delta = \sqrt{\frac{1}{\sigma \mu_0 f}} \]  \hspace{1cm} (6)

where \( \sigma \) and \( \mu \) are the conductivity and permeability of the liquid metal, respectively. Skin depth is the depth of the specimen at which the flux density value decreases to about one third of the maximum value.

![Figure 4: Examples of numerical models of magnetic flux densities from the center of the billet to the outer surface of the mould on a certain path under a) different electromagnetic frequencies with constant current intensity and b) different current intensities holding the frequency constant. See [5] for details.](image)

When the operating frequency is relatively high (50Hz or more), the skin depth in a LFEC process is extremely small and the force density significantly concentrated near the surface of the metal. A rapid change in magnetic flux density across a small skin depth means a large contribution of the potential component of the Lorentz force density in the narrow billet surface layer, which reduces the contact zone between the melt and the mould and decreases primary cooling intensity, so it is a desirable effect. But on the other hand, due to a small gradient of the magnetic flux density in the z-axis direction, the stirring effect in the liquid bulk (vertical convection) is weak. With frequency decreasing, the magnetic field density, induced currents and hence Lorentz force density increase throughout the bulk of the liquid metal and the forced convection (z-axis force density component) is enhanced, while the potential force component is reduced.

One of the most important things to consider is the optimal choice of frequency at given current intensity (bearing in mind the geometry of a certain problem). At the optimal frequency the best balance between both of the force density vector components is displayed, so an ideal flow pattern and temperature field are obtained.

Studies of industrial LFEC processes report that the optimal frequency range is between 15Hz and 30Hz.

A numerical model of the magnetic field density magnitude in a LFEC process is shown in Figure 4.

### 2.2 Heat Transfer

Casting of metals is closely related to heat release and heat transport during solidification and cooling. The rate of heat removal is very important as it determines the solidification time of the casting and the temperature distribution in the material during solidification. The third section deals with the effects of various temperature fields on the casting’s structure and therefore on its mechanical properties.
Heat transport and solidification processes in various casting processes are often very complicated. The number of variables in considerable. In order to facilitate the calculation of, firstly, the position of the solidification front as a function of time and, secondly, the temperature distribution and the temperature gradient as functions of positions, it is necessary to consider heat transport through the melt, two-phase region (mushy layer in Fig. 2), solid, and mould.

During casting the metal melt has a temperature that generally exceeds its melting point or solidus temperature. After casting, the melt solidifies and cools gradually because the surroundings, mainly the mould material, cool the cast metal. The metal is cooled most rapidly at the surface, which is in contact with the mould. Consequently the solidification starts at this surface and the solidification front, i.e. the interface between solid metal and melt, moves inwards into the melt. The solidification front is a solid-liquid interface in alloys that can be observed in Fig. 2.

The heat equation, giving the temperature spatial and temporal distribution, is an energy conservation equation that states that the change in energy is equal to the heat source minus the divergence of the diffusive heat flux. It is associated to the solution of the Fourier equation taking into account the contribution of the velocity field which describes convection phenomena (therefore it includes both conduction and convection):

$$\rho c_p \left( \frac{\partial T}{\partial t} + \bar{v} \cdot \nabla T \right) + \nabla \cdot \left( -k \nabla T \right) = q. \quad (7)$$

c$_p$ is the heat capacity of the fluid and $\rho$ its density, $q$ represents a source term. The simplified version of this equation is the diffusion equation.

There is a region between the melt and the solid phase that consists of a two-phase layer (the origin of this mushy layer is discussed in the third section). The temperature gradient influences the width of the mushy layer - the higher the gradient, the narrower the region. The established temperature field in LFEC will result in significant microstructure improvements compared to that of DC. Correct temperature distribution enables the prediction of the solidification front also.

2.3 Melt Motion

It has already been seen that the thermal and fluid mechanics problems are coupled through the velocity term $\bar{v}$ in equation 7. The velocity field is a solution of the Navier-Stokes equations:

$$\rho \frac{\partial \bar{v}}{\partial t} + \rho \bar{v} \cdot \nabla \bar{v} = -\nabla p + \eta \nabla^2 \bar{v} + \bar{f}, \quad (8)$$

where $\bar{v}$ is the velocity field, $p$ pressure, $\rho$ density and $\eta$ viscosity.

Maxwell’s equations are coupled to the fluid mechanics problem through the volume force density term $\bar{f}$. It represents the Lorentz force density term, calculated from the solutions of Maxwell’s equations.

2.4 Coupling of the Equations and Numerical Modeling of LFEC

Due to a great number of coupled equations and a variety of technological parameters that affect the process (geometry of the problem, casting temperature, casting speed, water flow rate, electromagnetic frequency and intensity and mould material among others) the LFEC problem is numerically simulated. Simulations help determine the best set of parameters in order to achieve the needed structure, but they also help understand the entire physics of the problem.

Numerical simulations for identifying the main characteristics of the developed flow pattern consist of solving the coupled problems which were discussed in the preceding subsections:

- the thermal problem to define the profile of the solidified front in order to estimate the shape and size of the stirred liquid pool (as an approximation, a liquid pool can be defined
through the identification of an isotherm at a certain temperature, that corresponds to the formation of a solid fraction up to a certain value),

- the electromagnetic problem to calculate the induced forces that alter the motion within the liquid pool,
- the fluid mechanics problem to define the flow patterns.

Some of the results from literature are given as an example.

Figure 5: Comparison of numerical results during DC (left half of each figure) and LFEC (right half) processes - temperature profiles (top left), velocity vectors with temperature contours (top right) and velocity patterns (bottom). See [6] for details.

Fig. 5 shows the temperature profiles, velocity vectors and velocity contours in the presence of the electromagnetic field and in the absence of it in three separate plots. The left parts of each subfigure are numerical results in the absence of the electromagnetic field and the right parts are results when the field is turned on.

Both the velocity vectors and profiles are entirely modified in the presence of the electromagnetic field. When the electromagnetic field is applied to the casting process, the flow direction in the melt is reversed and a small circulation is produced near the solidification front at the center of the billet. In addition, compared with that in the DC casting, the maximum velocity is increased several times and the location of its maximum is moved from the inlet region to the contact position between the melt and the mould. The phenomena are commonly explained by the forced convection resulting from the rotational component of the electromagnetic force.

Temperature profiles also exhibit a prominent modification when the field is applied. Firstly, it is observed that the temperature contours in the right part are shifted upwards relative to the
left part, which results in the sump shape being entirely modified and the sump depth being remarkably reduced (verified by results in another survey [7], see Fig. 6). In addition, compared with that in the absence of the electromagnetic field, the temperature in the bulk liquid is lower and more uniform. The reasons for the modification of the temperature field are the vigorous forced convection induced by the stirring and the increased heat flux along the horizontal direction due to the forced convection in the solidification front.

In conventional DC casting, the melt with a high temperature firstly reaches the solidification front after the melt is poured into the melt pool from the inlet region, and only then the contact region between the melt and the mould due to thermal buoyancy, therefore, the sump depth is relatively high in this process. What is more, because the flow velocity in the sump pool is very small, the heat transfer of the melt within the sump depends mainly on conduction, which results in an uneven temperature distribution in the melt pool. However, in the LFEC process, due to the electromagnetic field action, the high temperature melt from the inlet region firstly reaches the contact region between the melt and the mould along the free surface and its temperature is rapidly decreased. After it is cooled by the mould, the melt reaches the solidification front, which must result in the temperature at the solidification front being decreased and the sump depth becoming shallower as compared to the DC process. Above all, both conductive and convective heat transfer (the latter being dominant) are present, therefore the temperature distribution within the sump is more uniform than in the absence of the electromagnetic field.

When the frequency is at its optimum, the electromagnetic stirring is present throughout the metal melt bulk. If the frequency is above the optimal value, stirring (due to Lorentz forces) will be increased in the periphery region of the melt, but significantly decreased in other regions. On the other hand, if frequency is under the optimal value, the Lorentz forces are present in all of the melt, but are very weak because of the low magnetic field gradients.

3 Effects on Microstructure and Mechanical Properties

The premise of this section is that under optimal technological parameters of the LFEC process microstructure refinement and microsegregation reduction are the most obvious and thus lead to better mechanical properties of the cast material.

The first subsection describes how a solid is formed from a liquid. The second subsection describes how LFEC enhanced physical fields alter the conventional casting process and hence the material’s structure. The third subsection shows how microstructure is related to an important mechanical property.
3.1 Crystallization

During processing probably all metals and other materials go through a phase of liquid state. How the liquid melt solidifies is of utmost importance on the properties of the solidified material. Crystallization (as most liquids solidify) is a two step process. To begin with, all solidification starts by the formation of nuclei at various positions in the melt and the crystallites (which are also known as crystal grains) grow from these nuclei. The formation of stable crystallites is called nucleation. Secondly, nuclei grow larger using some kind of growth mechanism.

3.1.1 Nucleation

A material is expected to solidify when the liquid cools to just below its freezing temperature, because the energy associated with the crystalline structure of the solid is then less than the energy of the liquid. This energy difference between the liquid and the solid is the free energy per unit volume (\(\Delta G_v\)) and is the driving force for solidification.

When the solid forms a solid-liquid interface is created (Fig. 7). A surface free energy \(\sigma_{sl}\) is associated with this interface; the larger the solid, the greater the increase in surface energy. Thus, the total change in energy \(\Delta G\) of a spherical particle (shown in Fig. 7) is:

\[
\Delta G = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \sigma_{sl}
\]

where \(r\) is the radius of a spherical solid and \(\Delta G_v\) is the free energy change for the solidification process per unit volume, which is negative since the phase transformation is assumed to be thermodynamically feasible.

An embryo is a tiny particle of solid that forms from the liquid as atoms cluster together. The embryo is unstable, and may either grow into a stable nucleus or redissolve back into the liquid. When the solid is very small, with a radius less than the critical radius \(r^*\), further growth causes the total free energy to increase. The critical radius is the minimum size of a crystallite that must be formed by atoms clustering together in liquid before the solid particle is stable and begins to grow. The formation of embryos is a statistical process. If by chance an embryo forms which has a radius that is larger than \(r^*\), further growth causes the total energy to decrease. The new solid is then stable and sustainable since nucleation has occured, and growth of a stable solid particle (called a nucleus) begins.

The critical radius \(r^*\) can be found by differentiating the total energy with respect to sphere’s radius. The result is found to be \(r^* = 2\sigma_{sl}/|\Delta G_v|\).

The problem is that at thermodynamic solidification temperature, the probability of forming stable nuclei is extremely small, and solidification can not begin. When a pure sample is sufficiently
undercooled the probability increases and nuclei are formed. This is the principle of homogeneous nucleation.

Except in controlled laboratory experiments, homogeneous nucleation almost never occurs in liquids. Heterogeneous nucleation, which is nucleation on preexisting surfaces, is another mechanism for the formation of nuclei. Here, nucleation occurs on foreign particles or crystallites, so-called heterogeneities, which are precipitated in the melt. When crystallites are formed on these small heterogeneities, some of their surface energy supplies the required formation energy of the new crystallite.

Also important in the discussion of solidification is the rate of nucleation (number of nuclei formed per unit time). It is a function of temperature.

### 3.1.2 Growth Mechanisms

Once the solid nuclei of a phase form, growth begins to occur as more atoms become attached to the solid surface. The nature of the growth of the solid nuclei depends on how heat is removed from the molten material. There are two mechanisms describing how a nucleus grows: planar (eutectic) and dendritic growth.

If a liquid containing nucleating agents cools slightly under equilibrium conditions, there is no need for undercooling since heterogeneous nucleation can occur readily. Therefore, the temperature of the melt ahead of the solidification front is greater than the solidification temperature and the temperature of the solid is at or below the solidification temperature. During solidification, latent heat of fusion is removed by conduction from the solid-liquid interface through the solid. Any small protuberance that begins to grow on the interface is surrounded by liquid above the solidification temperature, so the growth of the protuberance stops until the remainder of the interface catches up. This mechanism is called planar growth and it occurs by the movement of a smooth or planar solid-liquid front into the liquid.

When nucleation is poor, the liquid has to be undercooled before a solid forms. Under these conditions, a small solid protuberance, which forms at the interface, is encouraged to grow since the liquid ahead of the solidification front is undercooled. Such a crystal aggregate is called a dendrite and is formed because its growth is favoured in certain directions. The undercooled liquid absorbs the latent heat of fusion in dendritic growth.

Solidification of alloys normally occurs by dendritic growth. The reason is not in the lack of nucleating agents, but is hidden in concentration differences of the alloying elements between the liquid close to the solidification front and the liquid further away.

Because diffusion is not immediate not even in the liquid, a boundary layer is formed in the liquid close to the solidification front due to rejected solute elements from the solidified part (more description in the following subsection). A boundary layer has a higher concentration of lower melting point elements not only than the solid at the solidification front, but also than the rest of the liquid behind the boundary layer. The boundary layer formed by rejection of the solute into the liquid may lead to a breakdown of planar growth (which is what could be expected in an industrial process because of the multitude of appropriate nucleating spots). Where there is a boundary layer in the liquid there must also be a variation of the liquidus temperature just ahead of the interface. Just ahead of the solidification front, the actual liquid temperature is lower than the liquidus temperature and the region ahead of the interface is constitutionally (compositionally) undercooled. This situation is not stable. If any area of the liquid interface happens to extend slightly ahead of the other areas, it will solidify faster and grow rapidly into the undercooled liquid. This is the principal cause of dendritic growth. A crystal grain consists of several dendrites.

If the thermal gradient in the melt is less than a critical value, constitutional undercooling will be present. The smaller the gradient, the larger the undercooling. If the temperature gradient is higher than the critical value, no undercooling can occur.
3.1.3 Microsegregation

Alloys in general do not crystallize at one temperature, the phase transitions occur at a temperature in a broader temperature band (see a schematic phase diagram of a binary alloy Fig. 8).

![Schematic Phase Diagram](image)

Figure 8: A schematic phase diagram of a binary alloy. Phase diagrams of alloys with more alloying elements can be far more complex.

The equilibrium final structure predicted by a phase diagram is achieved only if the cooling rate is extremely slow. Sufficient time must be permitted for the elements to diffuse and produce the compositions given by a phase diagram (this time can be evaluated from the diffusion constant and is estimated to be a few centuries [9]). In many practical situations, the cooling rate is too rapid to permit equilibrium. We therefore expect chemical segregation (nonuniform composition) in most castings made from alloys.

Microsegregation (also known as interdendritic segregation or coring) is a form of chemical segregation that occurs over short distances, often between small dendrite arms. The centers of the dendrites, which represent the first solid to freeze, are rich in higher melting point elements. The regions between the dendrites are rich in lower melting point materials, since these regions represent the last liquid parts to solidify. An unrealistically slow cooling rate would be required to allow enough time for diffusion in a solid to eliminate the concentration gradients. The compositions and properties of dendrite and interdendrite phases therefore differ. Moreover, denser dendritic network impedes interdendritic liquid motion, and the melt can not diffuse properly in this case. During solidification, this part of the melt forms an eutectic phase or an intermetallic compound is precipitated as a second phase. A structure with less dense dendrites will have less eutectic phases among grains.

3.2 Effect of LFEC on Microstructure

There are many aspects of how LFEC influences a material’s microstructure:

- significant grain refinement (finer grains as those formed by a DC process),
- microsegregation reduction (higher concentration of alloying elements inside crystal grains),
- macrosegregation reduction,
- better material surface.

A description of the first two aspects is given below.
It can be observed that the microstructure of the billets cast by a DC process is usually coarse and dendritic, but that in LFEC is fine and equiaxed. Coarse grains and heterogeneous grain distribution in a DC process and grain refinement in LFEC is obvious even on a macro scale (Fig. 9). The microstructures of the conventional DC billets have typical dendrite structure, while LFEC billet grains are homogeneous, fine and nearly equiaxed (Fig. 10, top figures). LFEC microstructure exhibits less non-equilibrium eutectic phases (Fig. 10, black area in bottom figures).

![Figure 9: Macrostructures of 7075 aluminum alloy billets with 150mm in diameter using DC (left) and LFEC (right) process. Grain refinement is obvious in a LFEC process. For details see [10].](image)

![Figure 10: Microstructures of 7075 aluminum alloy billets with 150mm in diameter using DC (both figures on the left) and LFEC (both figures on the right) process. The scale bar on the top figures is 100µm and 20µm on two bottom two. For details see [10].](image)

In a conventional DC process, the aim is to solidify the material as quickly as possible, since high cooling rates yield finer structure. This aspect is less important in LFEC, since microstructure refinement is achieved using other mechanisms.

Firstly, the effect of microstructure improvement of the LFEC process is due to forced convection. It was stated previously that electromagnetic body forces result in forced convection of the liquid. This enhances the so-called crystallite multiplication, meaning that parts of the dendrite skeleton are carried into the melt and serve as nuclei for new crystallites. Because of the melt’s movement, shear forces arise on the dendrite arms at the solidification front, and are great enough to break them and carry them into the melt. This increases nucleation rate as compared to that of the DC process.
Secondly, as shown in Fig. 5 (top left), the temperature in the sump pool during a LFEC process is quite uniform, so the thermal gradient is low. A decrease of the thermal gradient (if being under a critical value) results in an increase of constitutional undercooling and therefore dendrite growth, but dendrite fragments are constantly torn off from the solid-liquid interface because of shear forces of the melt.

Lastly, due to a rather uniform temperature distribution in the melt, the bulk of the melt is at comparable temperatures, so a more homogeneous growth of the formed nuclei is present. The temperature gradients in a DC process are much larger and hence some nuclei grow much faster than other, which results in a larger grain size dispersion.

If less nuclei are formed per unit time, the material structure will result in grain size being larger (as in a DC process structure), as compared to a high nucleation rate, when many nuclei are formed and grow simultaneously, resulting in an equiaxed grain structure.

Besides grain refinement, microsegregation reduction is another important consequence of a LFEC process. Due to effective mixing of the melt and fragmentation of dendrites at the solidification front during the LFEC process, microsegregation is reduced. This results in more alloying elements being within crystal grains and less eutectic phases being between them.

All in all, the effect LFEC is that the thermal gradient is significantly decreased, which increases constitutional undercooling and therefore dendrite growth rate, and that the forced convection is constantly fragmenting the dendrite tips to increase the rate of nucleation. At frequency optimum, the fragmenting is present at the highest fraction of the solidification layer. If frequency is not optimal, fragmenting is contrained to smaller portions of the layer, and the rate of nucleation is decreased, as compared to the optimum configuration. The average grain size and its dispersion are smaller.

3.3 From Microstructure to Mechanical Properties

Better microstructure (smaller grains and less microsegregation) lead to the improvement of mechanical properties of as-cast products.

One of the most important material’s mechanical properties is its yield strength $\sigma_y$. Yield strength is the minimum stress required to initiate plastic (permanent) deformation. The Hall-Petch equation relates the grain size to the yield strength:

$$\sigma_y = \sigma_0 + Kd^{-\frac{1}{2}}$$

where $d$ is the average grain diameter, and $\sigma_0$ and $K$ are material’s constants. It should be noted that the Hall-Petch equation is not valid for ultrafine or unusually large grains.

By reducing the grain size, the number of grains is increased and therefore the amount of grain boundary area. Any dislocation moves only a short distance before encountering a grain boundary and being stopped, and the strength of the material is increased ([8],[11]).

Through grain refinement LFEC therefore increases the yield strength of a material.

4 Proofs of Improved Material Structure

This section shows some of the experimental results performed by different researchers analyzing LFEC processes.

Fig. 11 displays Cu concentration profile along the billet’s cross section at different electromagnetic field intensities. It is obvious that a larger intensity leads to a more homogeneous structure of the billet, because liquid is effectively mixed during casting. Fig. 12 shows Cu concentration profile along the billet’s cross section at different electromagnetic field frequency. The best results are achieved at lower frequencies.
Figure 11: Effect of electromagnetic field intensity on Cu concentration profile through the billet’s cross section (a) and on average Cu concentration inside crystal grains (b) in a horizontal LFEC process. For details see [12].

Figure 12: Effect of electromagnetic field frequency on Cu concentration profile through the billet’s cross section (a) and on average Cu concentration inside crystal grains (b) in a horizontal LFEC process. For details see [12].

Figure 13: Effect of electromagnetic field intensity on grain size (a), grain size standard deviation (b), and hardness (c) under different operative conditions (frequency constant at 15Hz): S01 - 10A, S02 - 20A, S03 - 80A, S04 - 130A, S05 - 160A. R01 is an as-cast sample cast by DC, X01 is a DC cast and thermally homogenized sample. For details see [13].

Fig. 13 exhibits the effect of electromagnetic field intensity on average grain size, its standard deviation, and on material’s hardness. The ASTM G index is a logarithmical measure of the number of grains per unit surface, therefore a higher G index means a smaller average grain size. As expected, a higher intensity results in a smaller grain size and smaller standard deviation.
during a LFEC process. These values are quite homogeneous throughout the cross section of the aluminum alloy billet. An increase in hardness is also observed.

5 Summary

The appearance of LFEC (together with numerical modeling) in metallurgy is one of the landmarks among casting technologies in the last decades. It has to be emphasized that the field is not as limited solely to metallurgical engineers now as it once was. Physics plays an equally important role in the field, since empirical testing of operative configurations is both time and resources consuming (i.e. not economical). Therefore, a good model has to be established to give a meaningful description of the process. A few of the basic equations are given in this text, and it is obvious that even a basic model needs numerical simulations because of its complexity.

Due to current excellent results and good agreement between theoretical descriptions and final products, it is to be expected that LFEC becomes one of the leading manufacturing processes for the production of high quality materials.

References