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Electromagnetic Induced Segregation of Cast Parts

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Abstract

The Electromagnetic Induced Segregation (EIS) of cast parts is an innovative technology for diecasting of aluminium alloys. Using numerical simulation an inductor system has been developed to produce a primary Silicon concentration gradient during casting. The presentation shows the advantages using numerical simulation in research and development. A suitable inductor has been designed and its electromagnetic field optimized for EIS. The numerical model is 2D for geometries with cylindrical symmetry and 3D for non symmetric products. The inductor system is implemented into a pilot installation. With the metallurgical results the interaction between the electromagnetic field and the location of the primary silicon is investigated.

1. Motivation

In many technical application Functionally Graded Materials (FGM) promise advantage over conventional materials. Especially in the casting of light metals this technology offers innovative possibilities for wear-resistant but light products.

These materials consist of alloy composition gradients within the part, which promote different local properties. The main advantage is the possibility to control the characteristics locally.

2. EIS-technology

2.1 Physical fundamentals

Aluminum has eutectic concentration with 12,5% silicon. The melting point of this alloy is at 577°C. The solubility of silicon at this temperature is 1.65% and drops to 0,07% at 300°C. In an alloy with more silicon than this solubility there are mixed aluminum crystals and also silicon crystals. If the alloy cools down slowly the silicon solidifies in the eutectic alloy in the form of square-edged crystals, needles and plates. In the case of hypereutectic alloy the primary silicon accumulates to big crystals. With specific methods it is possible to decrease the size of the crystals but this reduces the loss of tensile strength and maximum strain only little. This is more disadvantageous at higher silicon concentration. In spite of this reasons alloys with concentrations up to 25% are used for wear resistant components, for example in the manufacture of internal combustion engines. The primary silicon produces with its hardness of 1400 HV a very good abrasion resistance.

Such a high concentration of silicon to increase durability and loading limit is not useful for complete cast parts.

With the technology of *Electromagnetic Induced Segregation* (EIS) a graded structure is generated, that could be adapted to the specific requirement of the product, for example to improve the abrasion resistance of the surface, without changing rigidity inside the material.

The process of EIS is based on the different electromagnetic force density between the components of the alloy, that are excited by the electromagnetic field. This is in consequence of the different electrical conductivities of the components. In the electromagnetic field the silicon particles with lower electrical conductivity are moved to higher flux density. This effect can be influenced by the frequency and the geometry of the electromagnetic field and the maximum flux density.

In cast parts which are produced with this technology the concentration of the primary silicon is dependent on the distribution of the magnetic flux density. One possible application is a magnetic field with rotational symmetry.

2.2 Description of segregation

Considering as example the process of segregation is described for a hollow cylinder. The inductor is located in the center of the cylinder, so that the region of interest is outside of the induction coil. The principle is shown in Fig. 1.

To demonstrate the effect of the electromagnetic field on the silicon particles it is necessary to describe the force density. Simplifying the magnetic field of a very long coil is assumed.

The flux density outside the coil is:

$$\vec{B}(r,t) = B_0 \cdot b(r) \cdot \vec{e}_z \cdot \sin(\omega t)$$

Here b(r) describes the radial decay of the flux density. The induced current density is:

$$\vec{S}(r,t) = S_0 \cdot s(r) \cdot \vec{e}_\varphi \cdot \cos(\omega t)$$

The current density has only components in azimuthal direction and the amplitude has radial dependence. The electromagnetic force density

$$\vec{f} = \vec{S} \times \vec{B}$$

is directed radial. For particles with lower conductivity follows with [1]

$$\vec{F}_{em} = -\frac{3}{2}\frac{\sigma_m - \sigma_p}{2\sigma_m + \sigma_p} V_p \vec{f}$$

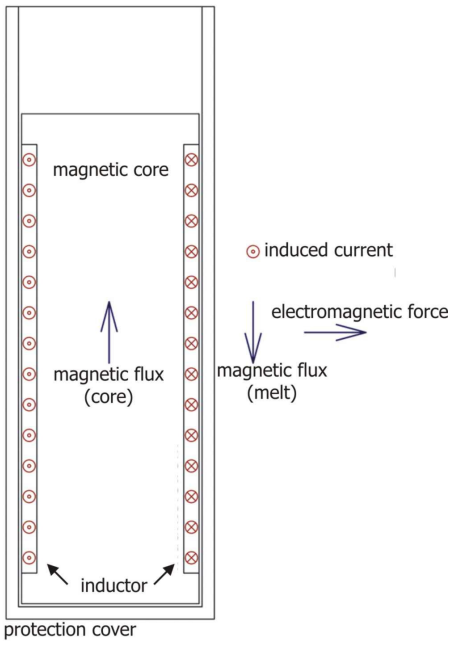

Fig. 1: Principle of EIS

that the resulting force on the particles is in negative radial direction. The force depends on the particles volume and the radial coordinate.

If a particle starts to move relative to the aluminum melt, a friction force counteracts the movement. This force depends on the viscosity of the melt, the size of the particle and the relative velocity from particle to the melt. If there is a balance between driving and retarding force, the movement becomes uniform. The flow ends when the melt solidifies, so the segregation varies with solidification time and local temperature distribution. Cooling is yet another parameter to adapt the segregation to the specific requirements of the product. Due to the water-cooled inductor the melt solidifies first on the protection surface of the inductor. In this regions (see Fig. 2, domain 1) the time for segregation is very short and there will be nearly no gradient. With larger distance to the surface the solidification time increases and the concentration with it. In Fig. 2 this is shown in domain 2. The shape of the silicon

concentration in this region can be influenced by the process parameters. Closed to this a depletion zone will appear where the primary silicon is removed from (3). Far away from the surface there will be a non affected area because of the limited penetration depth of the electromagnetic field (4)

2.3 Components of inductor system

Major task of the inductor system is to excite high magnetic field in the melt to initiate movement of primary silicon. A cooling system has also to be integrated into the inductor to dissipate heat from electric power loss and also to control the solidification of the melt.

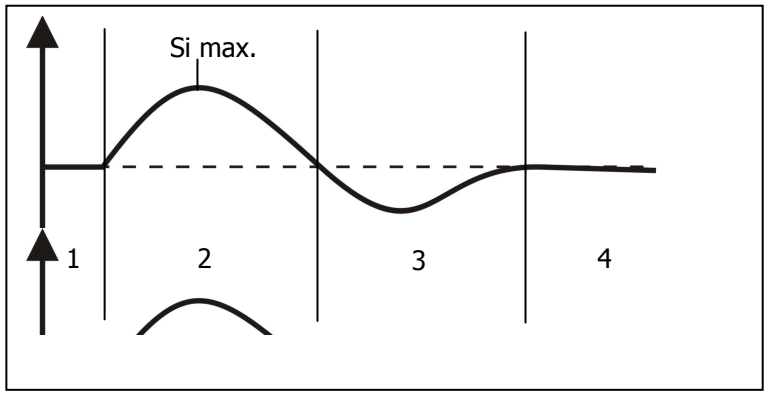

Fig. 2: Theoretical concentration of primary silicon

In Fig. 3 the numerical model of the developed inductor system is shown. In the center is a magnetic core to concentrate and guide the magnetic field. This core is surrounded by the inductor, which is made of a tube with rectangular shape to make maximum use of the limited space.

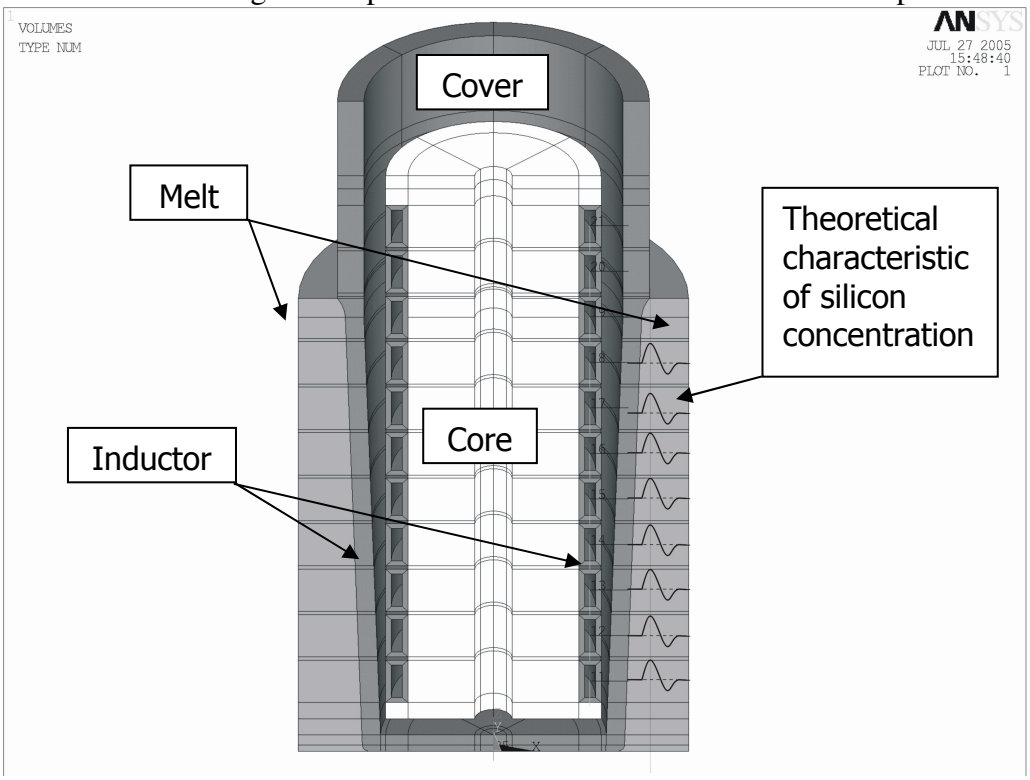

Fig. 3: Numerical model of inductor system

The cast part is a bushing with graded silicon concentration. The numerical model is used to calculate electric parameters of the inductor and for the dimensioning of the generator. Also the electromagnetic and thermal field is simulated to calculate the additional induced power. These results are input for the simulation of melt flow and solidification.

3. Results

3.1 Numerical Results

The simulations show that the magnetic flux density in the melt is high and uniform enough for the EIS-effect. As shown in Fig. 5 at the border between protection cover and melt there is maximum flux density of 180 mT possible. This is sufficient for segregation as it is already explored in preliminary tests.

In Fig. 7 the distribution of the flux density and the joule heat is shown, for a radial gradation of primary silicon only the axial component of the magnetic flux density is responsible. The additional energy that is induced into the melt is taken into account in the simulation of solidification.

Due to strong axial electromagnetic forces there is a melt flow that influences the segregation of the primary silicon. This flow seems to be important for a good quality of the products, so it has also been simulated to compare between melt velocity and distribution of primary silicon. The results of the melt flow simulation Fig. 4 show that regions with nearly no velocity corresdond with demixing zones of the primary silicon. These zones have to be avoided by an improved inductor design.

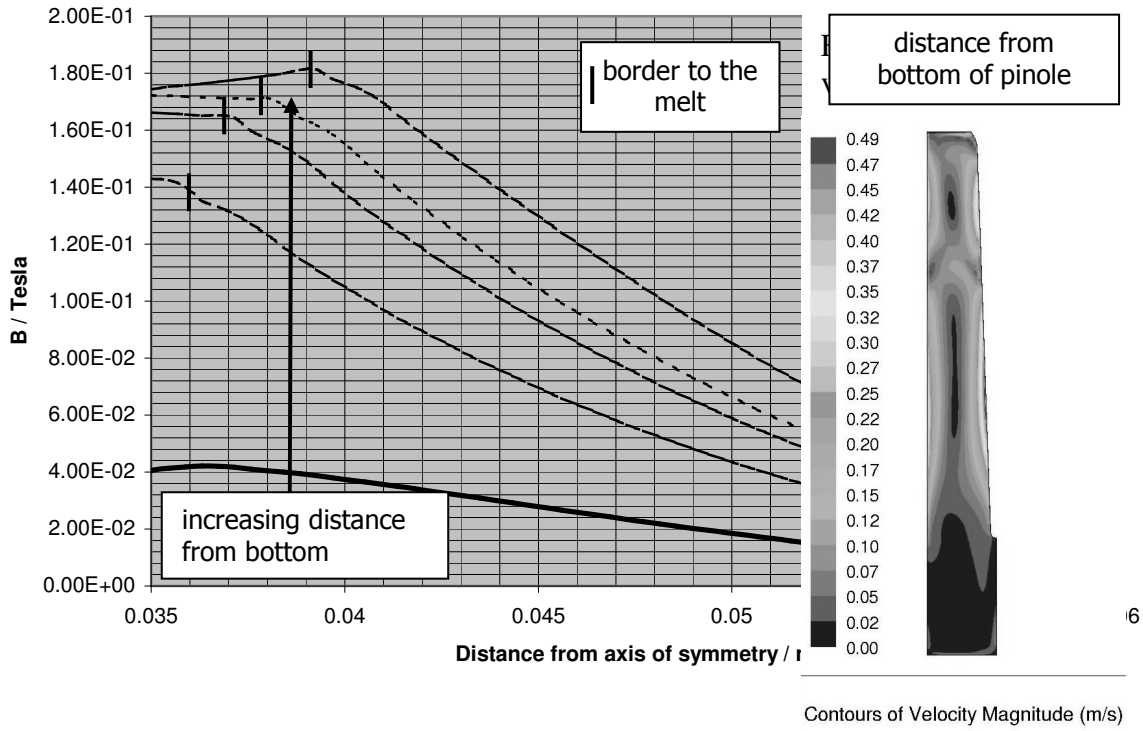

Fig. 5: Magnetic flux density in the melt

3.2 Casting Results

The micrograph of the casted bushing in Fig. 6 shows the effect of the EIS-technology. On the left side there are small crystals of primary silicon that are uniformly distributed

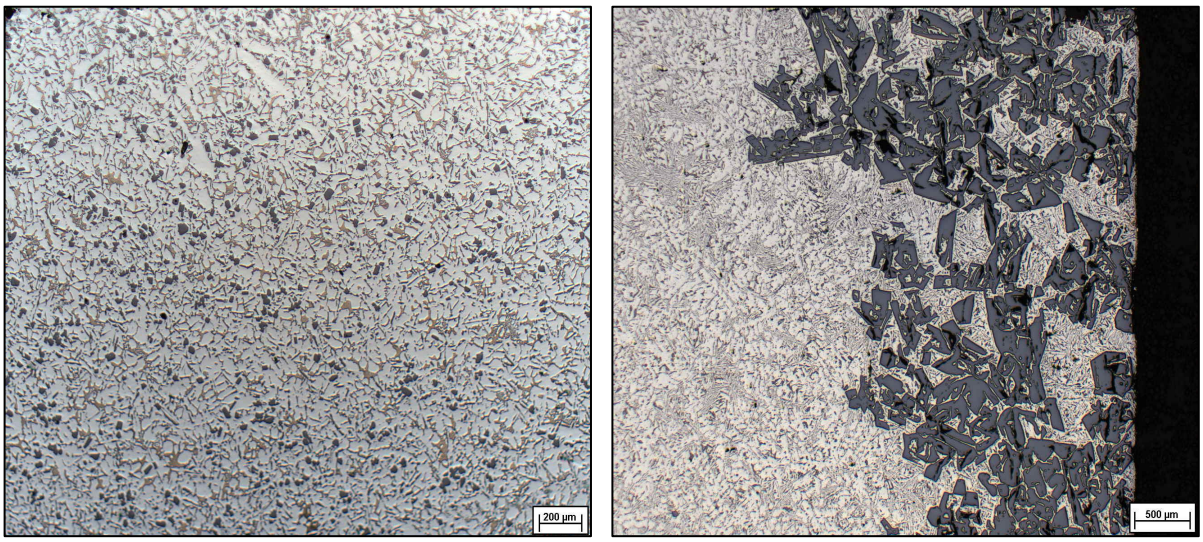

Fig. 6: Effect of EIS-technology (left: without, right: with electromagnetic field)

without EIS. With the influence of the electromagnetic field the crystals become larger and they concentrate on the surface as it is visible at the right micrograph. The distribution of the primary silicon is not yet optimal. The gradient in silicon concentration is very high and should become smoother to the one described in the theory of the segregation

4. Application

The EIS-technology is useful everywhere in aluminum casting where at present it is necessary to install additional bushings to achieve adequate wear resistance on the surface. Compared to hypereutectic alloys it is possible to achieve improved wear resistance with advanced usage properties.

In automotive application it is possible to produce wear resistant aluminum bores without subsequent coating or refining. So one step in machining is saved. And coevally the quality of the product in regions away from the surface is increased, because of the reduced silicon concentration. The EIS technology is still in experimental stage but experiments with realistic full scale products have already started.

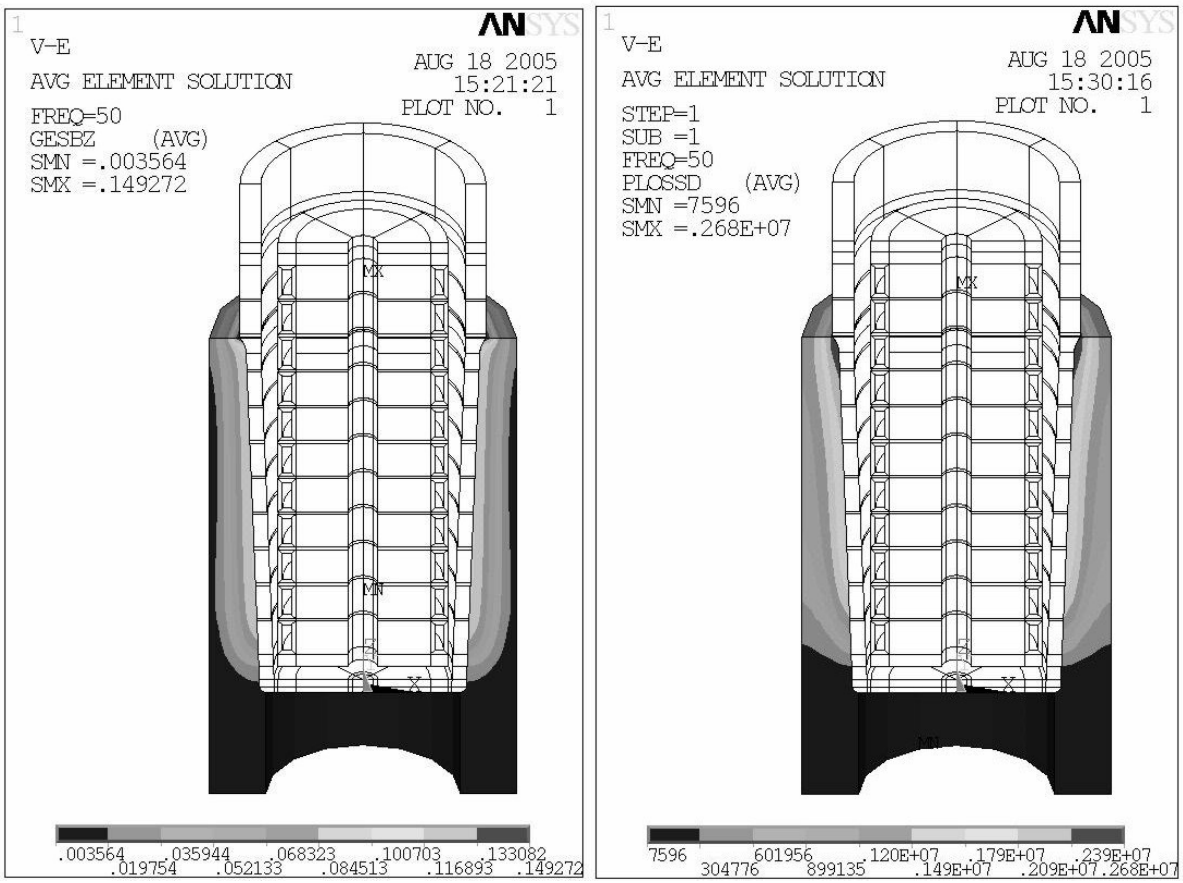

Fig. 7: Flux density (left) and joule heat distribution (right) in the melt

5. Outlook

At present the simulation refers to the electromagnetic and thermal field. And also the melt flow is simulated. A prediction of the silicon concentration is not possible in detail. This forecast highly depends on experimental results. This is due to different size of the silicon crystal that affect the electromagnetic forces. Larger crystals move faster than smaller ones.

In the future it should be possible to predict the impact of process parameters on the results. For this reason comprehensive studies have already begun. In parallel the simulation of the melt flow has started.

References

[1] Lennov, D & Kolin, A; Theory of Electromagnetophoresis. I.Magnetohydrodynamic Forces Experienced by Spherical and Symmetrically Oriented Cylindrical Particles, Journ. of Chemical Phys.

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