

Electromagnetically induced segregation for generation of a gradient microstructure in aluminium castings

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Introduction

There are three prevailing engine concepts for aluminium engine blocks. These concepts vary both in the selection of alloy and in the surface design of the cylinder bore.

Monolithic engine blocks consist of hypereutectic aluminium-silicon alloys. Typically AlSi17Cu4Mg alloys are used. The required mechanical resistivity is achieved by the high copper content. During solidification of the hypereutectic alloy primary-silicon crystals segregate and generate excellent tribological properties. For optimal utilisation of this effect the primary-silicon crystals are bared at the surface by subsequent machining. This could be for example made by honing⁽¹⁾.

Another concept is a quasi monolithic engine block. To achieve the required wear resistance the surface of the cylinder bore is built by infiltration of so called preforms or a special coating⁽²⁾. In this process the engine block could be casted from hypotectic or near eutectic alloys. The preforms are infiltrated by high pressure casting or squeeze casting. For coating, an atmospheric plasma sputtering or arc wire sputtering are used. For heterogeneous engine blocks cast iron bushings with scaled graphite are casted integral or assembled by thermal shrinkage. It is also possible to force in finish-worked cylinder-liners (slip-fit-bushings)⁽³⁾.

Great demands have been made on the mentioned concepts for engine blocks. Good mechanical properties, low wear at the cylinder surface, excellent tribological properties and certain process related requirements, like the need to be simple castable, rank among them. There is also the demand for low material usage and production costs.

It is obvious that all concepts have their own disadvantage. Monolithic engine blocks of alloys with 17% silicon content are brittle because of the primary-silicon crystals. As the surface of the cylinder bores has excellent tribological properties, subsequent machining of other regions of the block require great efforts because of the high durability. In quasimonolithic engine blocks the infiltrated preforms produce excellent tribological properties. But this technology requires additional steps during the process which increases the costs. When using slip-fit-bushings, different thermal expansion coefficients of bushing and engine have to be taken into account. In consequence during operation, deformation can appear and this has to be compensated by complicated adjustment of the piston and the piston-rings.

The disadvantages arise from different requirements on different regions of the engine block. The presented casting process should influence and control the microstructure and the mechanical properties of the part locally. The process is based on the physical phenomenon, that the position of the non-conducting primary-silicon crystals in conducting hypereutectic AlSi-alloy could be controlled. The crystals start to move into the regions with high magnetic flux density. This movement is initialised by electromagnetic forces. The different electrical resistivity of the semi-conducting Si-crystals and the aluminium-melt mean the forces between them are high⁽⁴⁾.

The aim of this process is to reduce the Si-content of the AlSi17Cu4Mg and simultaneously to increase the concentration at the surface of the cylinder bore by electromagnetic forces.

Description of silicon enrichment

The mode of action should be illustrated for this process on the basis of a cast part with rotational symmetry. The obtainable results are described in detail. The electromagnetic segregation effect arises in the exterior magnetic field of the inductor coil and the part should be a very long hollow cylinder with a gradient microstructure in radial direction.

To illustrate the effect of the electromagnetic field on the Si-crystals it is essential to describe the electromagnetic force density. The field of a very long coil is assumed (fig. 1).

The magnetic flux density is:

$$\vec{B}(r, t) = B_0 \cdot b(r) \cdot \vec{e}_z \cdot \sin(\omega t + \varphi\beta) \quad (1)$$

r radius of the coil

t time

B_0 maximum flux density at the surface of the cast part

b decay of the flux density in radial direction (in general exponential)

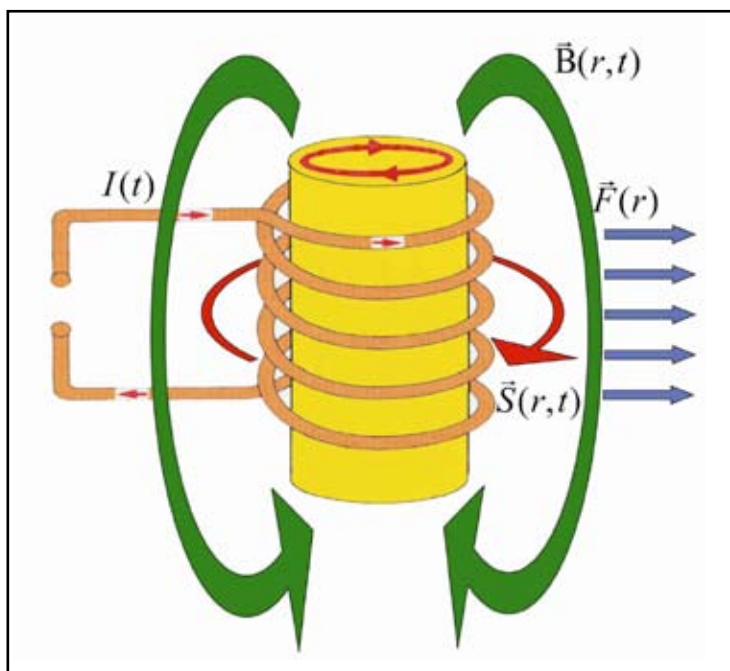


Fig. 1 Magnetic field of a coil showing the physical variables and vectors occurring

\vec{e}_z unit vector in axial direction
 ω angular frequency of current
 φ_B phase shift of magnetic flux density
 $b(r)$ describes the decay in radial direction. The current density is:

$$\vec{S}(r, t) = S_0 \cdot s(r) \cdot \vec{e}_\varphi \cdot \cos(\omega t + \varphi_s) \quad (2)$$

S_0 maximum induced current density at the surface of the cast part
 $s(r)$ decay of the current density in radial direction (in general exponential)
 e_φ unit vector in azimuthally direction
 φ_s phase shift of current density

The induced current density forms closed current in azimuthally direction with a decaying amplitude. The electromagnetic force density is:

$$\vec{f} = \vec{S} \times \vec{B} \quad (3)$$

In the region of the electromagnetic penetration depth, the time averaged force is directed, different from current density and magnetic flux density in radial direction.

The electromagnetic penetration depth δ is a measure of how far the electromagnetic field is penetrating into the aluminium. It is defined as the distance from the surface where the induced current density is declined to $1/e$ from their maximum value at the surface. The reason for this decay is the skin-effect.

The penetration depth δ depends on the angular frequency of the current ω and temperature dependent material properties, like electrical conductivity σ and magnetic permeability μ_r .

$$\delta = \sqrt{\frac{2}{\omega \mu_r \mu_0 \sigma}} \quad (4)$$

μ_0 magnetic permeability of air

The amplitude of the magnetic flux density only depends on the radial coordinate for long coils. As the magnetic force density also depends on the electrical properties of the material, there will be different force densities for the liquid aluminium and the solid Si-crystals. The resulting force between these two components is oriented inwards, so the crystals will start to move to the interior surface. The force is volume based. This effect was obtained and mathematically described by D Lennov and A Kolin⁽⁵⁾ in 1954. It is possible to describe the force acting on a Si-crystal as follows:

$$\vec{F}_k = \frac{3}{2} \frac{\sigma_s - \sigma_k}{2 \cdot \sigma_s + \sigma_k} V_k \cdot \vec{F} \quad (5)$$

In this equation the index 's' identifies variables belonging to the melt and all values with index 'k' are related to the Si-crystals.

If the movement of the crystals starts relative to the melt a frictional force counteracts the movement. This force depends on the viscosity of the melt and the relative velocity between melt and crystal. If a balance between these forces is reached a uniform movement without acceleration appears. This movement later ceases because of the solidification of the melt. So it can be controlled by cooling parameters. Directional solidification is very important for good segregation results. Modification of the cooling for the new thermal energy balance is one of the biggest challenges in this

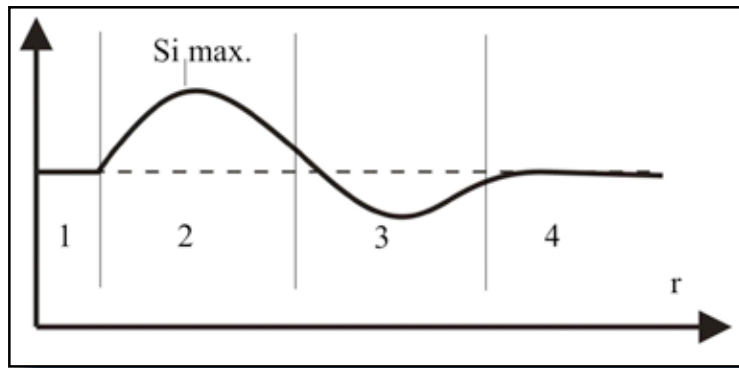


Fig. 2 Plot of primary-silicon concentration after segregation

project.

The electromagnetic forces do not only accelerate the crystals, the melt also starts to flow. By intensive flow other forces can act upon the particles. In strongly sheared fluids like that which the melt flow represents at the boundary, the Saffman-lift-force appears:

$$F_L = 6,46 \cdot \rho_s \frac{d_k^2}{2} \eta_s (v_s - v_k) \sqrt{\frac{dv}{dr}} \text{sng}\left(\frac{dv}{dr}\right) \quad (6)$$

ρ_s density of melt
 d_k diameter of crystal
 η_s viscosity of melt
 v_s velocity of melt
 v_k velocity of crystal
 sng algebraic sign of dv/dr

This force acts upon the crystals in the boundary layer perpendicular to the velocity. It is directed to the areas with higher velocities and depends on the diameter of the crystals. If they are assumed to be spherical, the relative velocity between crystal and melt, the density and viscosity of the melt as well as the gradient of the melt velocity, affect this force.

Saffman-lift-force and Stokes-force are implemented in numerical simulation tools and could be calculated from the melt flow. Consequently all forces are established and the crystal movement can be described.

$$\Rightarrow = \frac{dv_k}{dt} \frac{F_s + F_L + F_{em}}{m_p}$$

F_L Saffman-lift-force
 F_{em} Stokes-force
 m_p mass of particle

In this simplified model stationary observation is assumed, so all moments of inertia could be neglected.

In this case the shape of the resulting Si-concentration in the cast part leads to a four zone model (fig. 2). There will be a boundary layer originally concentrated at the surface (1). The shape of the enrichment layer (2) can be influenced by parameters of the electromagnetic field, like frequency, amplitude and power-on time of inductor as well as by casting related parameters. The depletion zone (3) is the region where the primary-silicon in the enrichment layer comes from. This zone is not very important in shape and intensity for the results. As the dimension of the cast part is big in comparison to the electromagnetic penetration depth, there will exist a not affected zone (4). This region will have original Si-content⁽⁶⁾.

Numerical simulation of electromagnetic field

The numerical model allows the calculation of electrical data of the inductor system to dimension the transformers for current, power and voltage. The power induced into the melt is also calculated to be taken into account during simulation of the solidification.

An essential parameter of the inductor system is the frequency of the current. In the field of induction heating, induction melting, induction hardening and crystal growing, the frequencies from several hundreds of Hz up to a few MHz are used. For the presented process only the forces are useful, the induced power changes the thermal balance during casting and

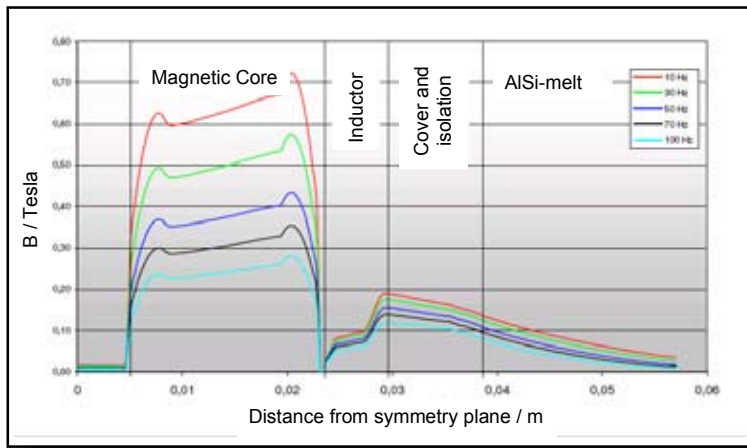


Fig. 3 Axial field density component as a function of distance from symmetry axis at various frequencies

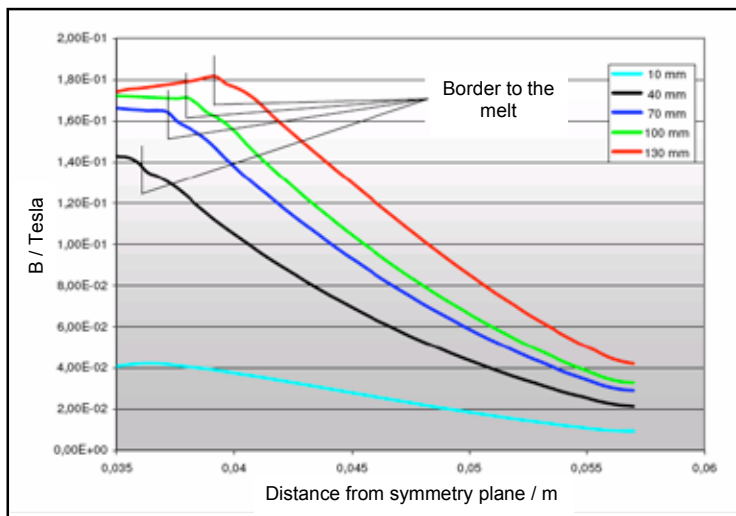


Fig. 5 Axial field density component as a function of distance from symmetry at various distances from the quill base

should be limited. For this reason only frequencies below 100 Hz are suitable for this process.

In fig. 3 the flux density is shown for frequencies between 10 Hz and 100 Hz. There are four domains in the diagram. In fig. 4 the developed inductor system is shown and the domains can be located. The centre of the inductor (fig. 4) corresponds to the origin of the axes in fig. 3. In the centre, the tube for cooling water is integrated, adjacent is the magnetic core made of magnetic compound material. In this area the magnetic flux density is much higher than in the other regions, because of the high permeability of the material. In the diagram only the axial component of the flux density is shown, because it has the main impact on the segregation result. The water-cooled inductor coil wraps the magnetic core. The flux density there is lower. To protect the inductor from the high temperature melt a cover made from stainless steel encases the coil. The parameter in this diagram is the frequency. Obviously the flux density in the magnetic core increases with decreasing frequency, resulting from the weakening of the skin effect, which depends on the frequency. In the melt the difference in flux density is not significant. To prevent the magnetic core from saturation the frequency was selected to 50 Hz.

From preliminary investigation the required flux density was already known, hence the necessary current could be found by the simulation. The flux density increases linearly to the current, as long as saturation effects could be neglected. Current starts to be effective from 1000 A. For a coil with a radius of 100 mm a very precise current feed has to be developed. The voltage of 5 V is low because of the low frequency and the small number of turns. The handling of these low voltages is innocuous.

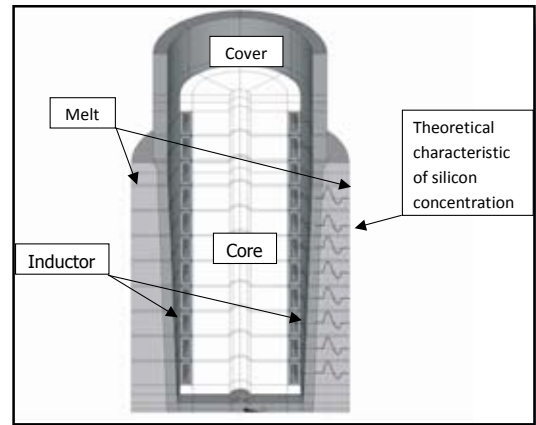


Fig. 4 Sketch of the developed inductor system



Fig. 6 Test object for electromagnetic induced segregation process

The magnetic flux density in the melt is demonstrated in fig. 5. The parameter in this diagram is the height above the lower border of the cast part. To achieve a uniform flux distribution the coil is longer than the cast part and its top protrudes the cast part. The flux density at the height of 10 mm (light blue graph) is lower than in other regions. But in this special application it is not possible to use a lower extension to ensure a uniform flux density distribution. In all other regions the values are high enough.

To improve the accuracy of the model a simplified numerical model of a BMW V8 engine has been developed. In fig. 6 the original engine is shown. For simplification it is reasonable to reduce the model to one half of cylinder. This corresponds to 1/16 of the original engine. Almost all effects which appear can be observed, especially for the electromagnetic field. Fig. 7 shows the developed numerical model that has been mirrored two times to build a virtual 3D-model of a 2 cylinder engine. But typical regions of the original engine are included in the simplified version. These regions are:

- region between protection cover and the water cooling jacket (fig. 7⁽¹⁾)

- region between two cylinder bores (fig. 7⁽²⁾)
- region from protection cover to environment (fig. 7⁽³⁾)

With this improved numerical model it is possible to distinguish the electromagnetic characteristics of each region concerning the magnetic flux density, the induced power density, the magnetic force density and the induced current density.

In fig. 8 the results from 3D-reduced model calculations are demonstrated. An important question was the effect in the small bridge between the cylinder bores. There magnetic fields from two inductors are superimposed in this region. In fig. 8 it can be seen that only the magnetic flux densities are added in bridge region, all other quantities cancel each other out. Because the induced force density is the cross-product of current-density and flux-density (equ. 3). There are no forces at the symmetry plane between the cylinder bores.

Experiments on full-scale engine block

Having tested the technology at a small scale test, it was necessary to test its suitability for mass production. Due to the solidification time for this process could only be performed by low-pressure chill casting or sand-casting. Further on the inductor system should be added to an installation that is already in operation for serial production. At KS -Technologie AG, Neckarsulm a V8 die was prepared for experiments on a full-scale cast part. One quill was substituted by one with integrated inductor system. The required energy supply was realised by transformers, which are integrated into the low-pressure casting machine. The voltage and current of the transformer was controlled by the machine control.

By the back fitting of the die completely new cooling parameters for the engine block have to be found. To give proof of this a simulation of the solidification together with the induced power was carried out. Fig. 9 shows the difference between solidification without electromagnetic field and with the power induced by the inductor. By the energy of the electromagnetic field and the change in the design of the die the thermal behaviour of the system was affected in a negative way. In parts of the engine necking can appear and the possibility for blowholes increases. The cooling parameters for casting with one or more inductors have to be adjusted carefully to prevent blowholes.

Parameters investigated by preliminary small-scale test at ACCESS, Aachen have been used for the first full-scale experiments. All hitherto existing results and further estimations indicate that electromagnetic induced segregation in a serial die is possible with the utmost probability. Modification of the die was forgone. Experiments with one, two and four inductors were carried out.

To control the location of the primary-silicon crystals parametric study was undertaken. The first parameters were the power-on time and the current amplitude. It was discovered that the current affects the width of the enrichment layer but only on a limited scale. The first experiments show that not only the width but also the concentration depends on the current amplitude. Fig. 10 shows a micrograph of the cylinder wall. Obviously, the magnetic field has produced an enrichment zone and also a depletion zone. The concentration of the

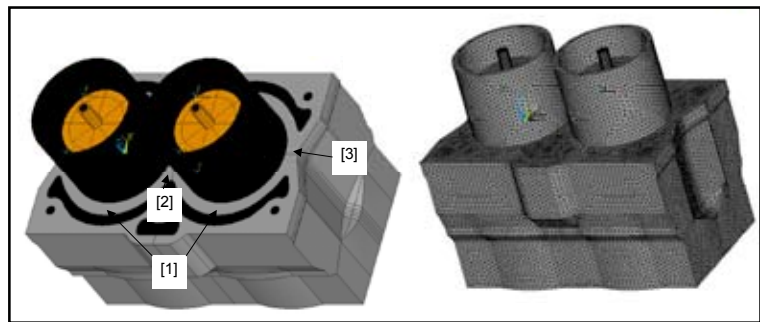


Fig. 7 Simplified model and numerical mesh for BMW V8

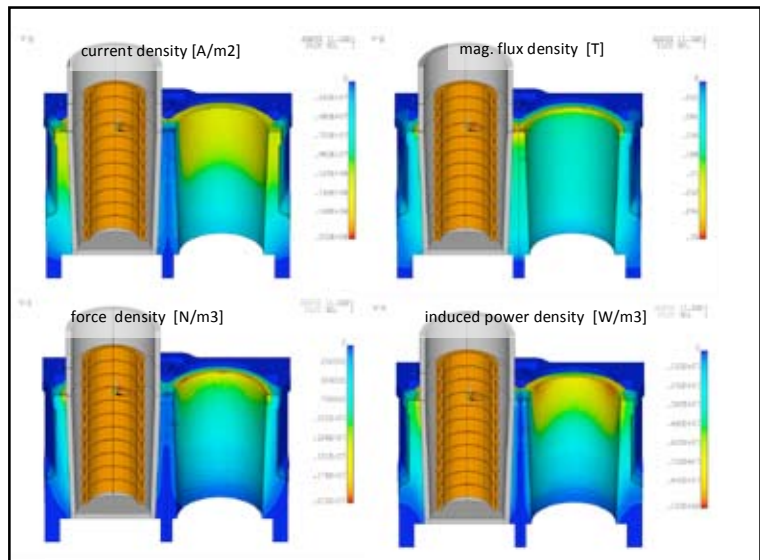


Fig. 8 Results from numerical 3D calculation for simplified V8 engine

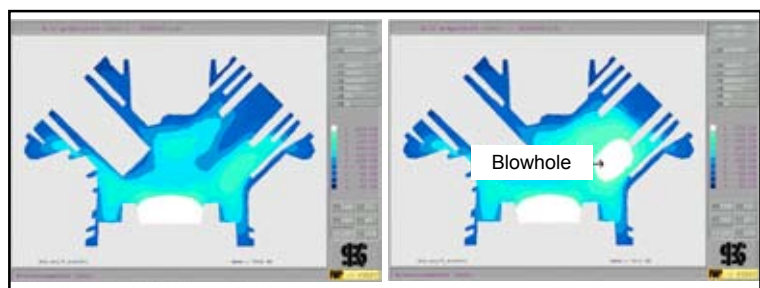


Fig. 9 Comparative assessment of solidification times in the standard process (a) and using an electromagnetic induced segregation quill

primary-silicon is high enough but the distribution is not yet optimal. The enrichment zone contains regions with less primary-silicon and the depletion zone contains regions with clouds of primary-silicon crystals. But the interface between these two zones is very well distinguishable.

In fig. 11 this transition between the zone with primary-silicon and without is shown (5 times scaled). The transition is abrupt but the microstructure meets all demands for porosity, size and amount of crystals and distribution of primary-silicon.

During analysis of the primary-silicon concentration inside the enrichment zone it was found out, that some regions have doubled concentration compared to engines cast by common technologies. Table 1 shows the detailed results of this analysis. It should be noted that the depth of the enrichment layer is not yet high enough. Depending on the grinding allowance the enrichment layer is removed during subsequent machining. For successful introduction to serial process this depth has to be increased. Also the distribution in radial and axial direction has to be improved. A uniform segregation could not be observed repeatable for all equipped

Property	Enrichment zone AlSi14Cu4Mg	Comparison AlSi17Cu4Mg
Primary-silicon content (surface ratio)	12-22%	8-12%
Eutectic-silicon content	8-10%	8-10%
Average diameter of primary-silicon crystals	32-34µm	36-42µm
Depth of enrichment layer	0.9 - 2.6 mm	-

Comparative assessment of microstructure characteristics data for an alloy treated using the electromagnetic induced separation process and a standard alloy

cylinders.

Nevertheless, a BMW V8 engine could be assembled and checked on an engine test bench. After this test run the complete engine was disassembled and the walls of the cylinder were inspected. To summarise, no difference between engines cast with common technologies and the test engine could be found and the advantages of this new technology prevail, because other regions have less primary-silicon and costs for subsequent machining could be saved. Additional installations are reduced to new sleeves with inductors inside and transformers.

Conclusion

The EIS-technology allows an effective segregation of silicon crystals at the surface of cylinder bores. The Si-content of the used hypereutectic alloy could be reduced without changing properties of the surface. Important process parameters are: the temperature of the melt, thermal balance of the die, power and current of inductor, cooling of the sleeves, die-fill time and the casting pressure. With suitable casting parameters it is possible to produce cylinder surfaces by electromagnetic induced segregation that are on a par with common cylinder surfaces.

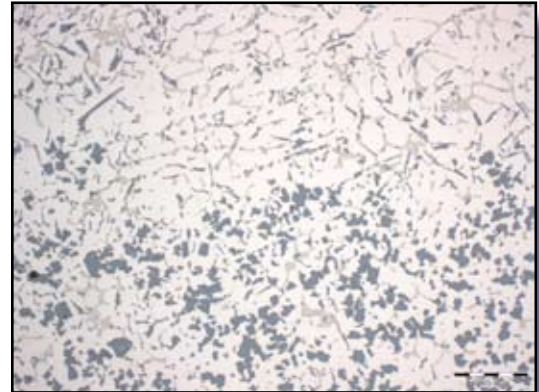


Fig. 11 Transition from primary-silicon accumulation zone to the lower-primary silicon zone

Acknowledgement

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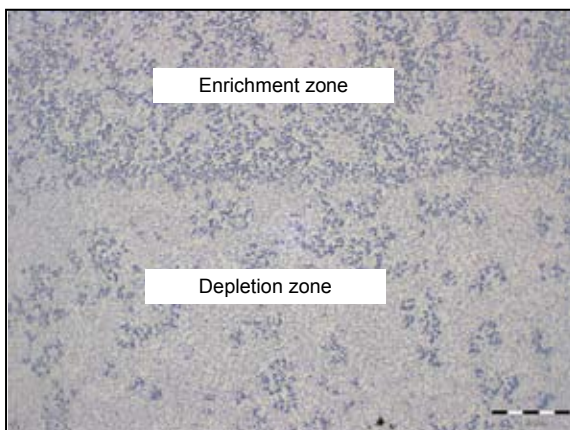


Fig.10 Microsection through a cylinder wall with application of an electromagnetic field

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