Semi-Solid Processing by Electric Current During Sand Casting of Aluminium Alloys

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Abstract. This study reports the effect of DC and 50Hz AC treatment (ECT) on aluminium or aluminium alloys during solidification in sand moulds i.e., at their semisolid state. Castings, with different geometry, were made in open or closed sand moulds. It is observed that ECT (a) reduces dissolved gas, (b) reduces internal shrinkage and (c) metal mould reactions in castings. It is also observed that the AC treatment is more effective compared to DC treatment. ECT changes the movement of solidification front. The optical microstructures of ECT samples are quite similar to the samples treated in other semisolid processing methods.

Keywords: Semi Solid Sand Casting, Electric Current Treatment, Aluminium Alloys, Sand Casting, Grain Refinement

1. Introduction

Normally, molten metal is treated with inoculants to refine or modify cast microstructures to improve properties of cast components. Due to multiple recycling of scraps, the inoculants form debris and discarded permanently. Alternatively, molten metal is treated in its semisolid state (i.e., in between the liquidus and solidus temperatures of the alloy) to refine/modify cast microstructures. Campbell [1] reviewed the effect of vibration during solidification. Flemings [2] reported that the increased convection and slow cooling leads to formation of spherical grains that possess rheological properties in the semisolid state. They behave thixotropically and viscosity can be varied over a wide range. The metal structure and its rheological properties are retained after solidification and partial remelting. The semisolid alloys can be formed by semisolid metal forming process to produce metal components. Several authors [3-6] reported the effect of different types of electromagnetic stirring (EMS) during solidification of aluminium alloys. During EMS, the strong fluid flow (i) detaches the dendrites from the solid liquid interface, (ii) fragments and (iii) carries them into the melt to form slurry. In rotating EMS (REMS)[3], the stirring increases cooling rate, therefore, dendritic arm spacing is reduced due to undercooling. Additionally, the grain size is also reduced because the fragmented dendrite debris acts as nucleation centres. The linear EMS(LEMS)[4], operates in the same way as induction furnace, the melt turns to slurry consisted of fragmented dendrites globular solid phase surrounded by lower melting point (eutectic) phase. The shape of the fragmented dendrites changes with variation of the frequency of EMS [5-6]. Low frequency AC favours large equiaxed dendrites. Dendrites are fragmented and refined by intermediate frequency AC (up to 1.5 kHz) but highfrequency AC (10kHz) promotes columnar dendrite formation. These materials, when partially remelted, offers less resistance to flow even at high solid fraction. This property is used to process the material in pressure die casting or forging (known as SSM). Electro-hydro-dynamics (EHD) or electro-fluid-dynamics (EFD) [7 - 9] is the study of the dynamics of
Electrically charged fluids. The external electric field, when applied on a fluid, induces fluid motion as the fluid bears a net electrostatic charge. It induces both normal and tangential forces on a fluid interface. The flow rate is linear in the electric field. The force acting on the fluid is given by the equation:

\[ F = \frac{I d}{k} \]  

Where,
- \( F \) is the resulting force (Newtons)
- \( I \) is the current flow (amperes)
- \( d \) is the distance between electrodes (meters)
- \( k \) is the ion mobility coefficient of the dielectric fluid (m²/Volt sec).

In general, the phenomena relates to the direct conversion of electrical energy into kinetic energy. The author [10], reported the effect of ECT during solidification of 99.5% Al. The melts (in semisolid state) are (a) treated in linear electromagnetic field (LEMS), (b) treated with 50 Hz AC electric current (ECT) and then compared with the sample without any treatment. It is observed that both LEMS and ECT (a) reduces the freezing temperature, (b) increases the heat transfer rate but (c) the LEMS process consumes more energy compared to ECT. Therefore, further studies [11-14] were conducted with ECT (AC / DC) on different compositions of Al-alloys and patented [15]. These studies revealed that the ECT on aluminium alloys:
- i) reduces shrinkage pipe formation (LM-0),
- ii) modifies columnar structures to equiaxed (LM-0),
- iii) refines eutectic silicon (LM-6 & LM-25),
- iv) increases volume fraction of primary \( \alpha \)-phase and reduces volume fraction of eutectic phase (LM-6, LM-25, LM-30)
- v) reduces pinhole porosity (to minimum) at an intermediate range of current but it increases with increased current.
- vi) improves machinability of LM-6 and LM-30 alloys due to refinement of eutectic silicon and primary silicon cuboids.

1.1. Objectives

Normally, SSM is done in pressure die-casting route. This process is quite complex and requires huge infrastructures that involve cost. Moreover, the flexibility of making shaped casting is limited in SSM. The objective of this study is to develop a cheaper SSM method for sand-casting foundries. This study explores:
- i) The effect of ECT (DC / AC) on removal of internal shrinkage or gas porosity in castings.
- ii) Microstructural modifications and reduction of metal-mould reactions.
- iii) Energy consumption for this process

2. Materials and Methods

2.1 Castings made in open sand moulds

These moulds were made using bentonite and moisture as binders. During mould preparation (for ECT) the pattern was placed inside of a steel frame (i.e. mould box). A graphite rod (~ 0.01 m dia) was placed at one corner of the pattern and the frame was filled with sand mixture and rammed. The mould was properly vented. The extended graphite rod was cut after keeping a gap of 0.025 m from the sand surface for electrical connections. The mould box (along with pattern and sand) turned upside down and the wooden pattern was removed. The inside part of graphite rod becomes visible from the top. The bottom part of the graphite rod was connected to power supply unit. One mould was made without any graphite connector for normal casting.

Commercial purity (99.5%Al; LM - 0) aluminium (~ 1 Kg.) was melted in a medium frequency air induction furnace with graphite lining. The melt was superheated (~ 750°C) and poured into a preheated...
(\(\sim 300^\circ\text{C}\)) clay graphite crucible without any degassing treatment. A graphite rod was used to clean oxide layer formed on the melt-surface and poured in sand mould and solidified.

For ECT, the moulds with graphite connectors were used. The graphite rod was connected to one pole of either DC or AC power supply unit by insulated copper wire. The other pole was connected to another graphite rod with copper wire. After pouring liquid metal into mould, the second graphite rod was connected to molten metal. Then the power supply unit was switched on and its voltage was adjusted (manually) to flow desired amount of current through the liquid metal. The power supply was switched off (manually) at the end of solidification. This process is repeated with different current intensity.

2.2. Study on castings made in closed (Cope and Drag) sand moulds

The moulding process, the charge material and the melting process were same as mentioned above. In two-part moulds, the graphite rods were embedded in both moulds. The electrodes were placed along the bodydiagonal of the pattern. Fig. 1 shows electrical connection to the electrode embedded at cope and pouring of molten aluminium in a mould. The electricity was switched on only after complete filling of the mould and the current was adjusted accordingly. However, it was disconnected automatically as the casting contracts after solidification and detached from the electrode. Except sample 1, other samples were treated with increased AC. All samples were cut along the marked line to see the effect of current treatment on porosity and internal shrinkage.

![Fig. 1. Melt is poured in a closed sand mould for electric current treatment](image)

2.3. Study on hollow cylindrical castings

Trials were also conducted on hollow cylindrical castings with length 0.175 m X 0.075 m (i.d.) X 0.025 m (wall thickness) as shown in Fig. 2. LM-4 (Al-4Cu-5Si-0.8Fe-0.2Mg) alloy ingot pieces were melted in a gas fired melting unit and superheated to \(\sim 800^\circ\text{C}\). The melts were not degassed. Riser free castings were made in sodium-silicate-CO\(_2\) bonded sand moulds with bottom pouring arrangements. Except sample 0, all other castings were treated with varying AC current. The details of electrical connection and application of electric current were mentioned in 2.1. After removal of casting (Fig. 2a) from sand moulds, \(\sim 0.05\) m from the top of each casting was cut (Fig. 2b & c) for visual inspection of both inside and outside surfaces. Then \(\sim 0.025\) m thick sections were cut from each ring for estimation of (i) external shrinkage, (ii) gas porosity and (iii) microstructural studies. Samples for hydrogen gas analysis were cut from each casting (0.003 X 0.003 X 0.01 m\(^3\)) and analysed in a LECO hydrogen determinater (RH - 402). Three samples were etched in a solution consisted of 10 ml HCl, 30 ml HNO\(_3\), 5 ml HF and 55 ml ethyl alcohol (dehydrated). Specific gravity of these samples was measured by water-immersion method.

3. Results
3.1. Study on castings made in single (Open) sand mould

Fig 3 shows visual appearance of the castings. Sample 1 was cast without any treatment. Samples 2–5 were treated with 2–5A AC respectively. Similarly, samples 6–9 were treated with 2–5 A DC respectively. All castings were sectioned through its middle along their length (as marked on sample 2) to see the effect of electric current on internal shrinkage.

Fig. 2: (a) Hollow cylindrical casting with 0.075 m (I.D.), 0.025 m wall thickness and 0.175 m long. Sections from the top part of castings (b) without current treatment, (c) with current treatment
Fig. 3: Open castings with increased (a) AC and (b) DC current treatment. Castings were sectioned along the black line and shown in the next figure.

Fig. 4 shows the cross sections of castings without and with ECT (DC / AC). The untreated sample (Fig. 4a) shows that the internal shrinkage extends along horizontal and vertical directions. Figs. 4b - e show the internal shrinkage of AC treated samples. It is observed from the figures that
i) Low intensity AC eliminates shrinkage in a casting (Fig. 4b)
ii) It increases with increased current (Fig. 4c-e).
iii) It extends along the current flow direction.
iv) The inside surface of the shrinkage is smooth.
However, the effect of DC treatment on internal shrinkage is shown in Figs. 4f – i. The figures show that:

i) The shrinkage cannot be eliminated by DC treatment.
ii) It also extended along the current flow direction
iii) The inside surface of shrinkage is rough.

3.2. Study on castings made in closed (Cope and Drag) sand moulds

Fig. 5 shows a set of castings (~ 0.025 m dia) made in closed box sand moulds. All samples were sectioned along the marked line as shown (on sample 5).
Fig. 6 shows the cross sections of AC treated castings. The untreated sample (No. 1) shows gas porosity and shrinkage marked as a circled zone ‘A’ (Fig. 6a). However, low intensity current treatment (sample 4, Fig. 6b) reduces both shrinkage and gas porosity to minimum. But at higher current (sample 6, Fig. 6c) the gas porosity (marked as ‘A’) reappears at casting sections. The figure also shows that the gas porosities are aligned parallels on casting section i.e., the direction of current flow.

3.3. Study on hollow cylindrical castings
Fig. 7 shows typical shrinkage profile of untreated and AC treated samples. The untreated sample (No. 0) shows that more shrinkage at inner (core) side of the casting compared to the outer (wall) side of the casting. However, in current treated samples (No. 2, 3, 5 & 6), the extent of shrinkage is same irrespective of the sides.
Fig. 7: Shrinkage at the top of castings sections. 0: No treatment; 2: 2A AC, 3: 3A AC, 5: 5A AC and 6: 6A AC treatment. The left of each sample is the inner surface and the right of each sample is the outer surface of castings.

Fig. 8 shows the appearance of inside and outside surfaces of top part of the untreated sample (No. 0). The inside surface of the casting (Fig. 8a) appears dull due to sand sticking but the outside surface (Fig. 8b) is free from such defect.

Fig. 8: Casting surfaces of untreated samples (No. 0): (a) the inside surface and (b) the outside surface.

Fig. 9 shows that the inside surface of sample 2 (with 2A ECT) is free from sand sticking. Fig 10 shows typical parallel lines on casting surface on sample 5 (with 5A ECT).
Fig. 9: Inside casting surface of sample 2.  Fig. 10: Bands on casting surface Sample 5

Fig. 11(a-e) show the effect of increased current on (a) gas porosity and (b) hydrogen content in castings made without and with ECT. The untreated sample (No. 0; Fig. 11a) shows maximum porosity. However, low intensity ECT (Fig. 11b) significantly reduces gas porosity (sample 2). But it reappears with increased treatment current (Fig. 11c-e).

(a) Hydrogen: 3.1 ppm

(b) Hydrogen: 1.0 ppm
(c) Hydrogen: 1.2 ppm
Fig. 11: Samples show variation in hydrogen gas porosity in castings without and with AC current treatment: (a) Sample 0 (no current), (b) Sample 2 (2A), (c) Sample 3 (3A), (d) Sample 5 (5A) and (e) Sample 6 (6A).

Fig. 12 shows optical microstructures of samples without and with current treatment. The untreated sample (No 0, Fig. 12a) shows coarse dendrites. But low intensity ECT (Fig. 12b, sample 2) fragments primary dendrites. Some fraction of dendrites becomes globular. The fragmented dendrites become coarser by increased current intensity (sample 3, Fig. 12c).

Fig. 12: Optical microstructures of the samples (without degassing) treated without and with AC current.
Table I shows a comparative data of the energy consumption for different semisolid casting processes with aluminium alloys.

| Reference       | Method          | Weight of Metal, Kg | Wattage, Watts | Time, Sec | Total, Wh | Specific Wh/Kg |
|-----------------|-----------------|---------------------|----------------|-----------|-----------|----------------|
| Maity[22]       | Mechanical Stirring | 1                   | 750            | 900       | 187.5     | ~ 185          |
| Mondal[23]      | Do              | 3                   | 5000           | 600       | 375       | ~125           |
| Dutta et al [4] | LEMS            | 10                  | 750            | 1800      | 833       | ~83            |
| This study      | ECT             | 3.7                 | 40             | 500       | 5.55      | ~1             |

4. Discussion

This study compares the effect of EHD [7-9] or ECT [10-17, 19, 21] during solidification (i.e., at the semisolid state) of 99.5% Al and LM-4 Al-alloy in sand moulds. It also reports the effect of ECT on castings with different geometry, energy consumption, modification of cast microstructures etc.

4.1. Study on castings made in open sand moulds

It is evident from Fig. 4 (a-i) that ECT (AC/ DC) plays a significant role in the formation of internal shrinkage in castings. Normal casting (No. 1, Fig. 4a) undergoes shrinkage along vertical and horizontal directions. This is due to the movement of solidification fronts from the bottom as well as from the mould walls. However, 2A AC ECT produces shrinkage-free castings (Fig. 4b). The ECT increases the EHD [7-9] force that increases flow of molten metal. It feeds internal shrinkage that forms during the progress of solidification in a casting. In EHD, the current flow enhances the fluid flow along the peripheral region of the conducting fluid. Therefore, heat transfer rate is increased [10] that suppresses the freezing point and favours early solidification of melt [11-13]. However, Fig. 4(c–i) show that increased ECT produces elongated shrinkage along the current flow direction. This is in addition to the external shrinkage of samples as shown in Fig. 3. This is the effect of increased fluid flow along the peripheral region of the casting. Here the top surface of the casting (in contact with air) solidified earlier rather than feeding the melt into the shrinkage cavity. Dutta et al [4], reported similar phenomena when castings made with linear electro-magnetic stirring (LEMS). They reported early solidification of the upper part of the casting compared to untreated casting, therefore, the entrapped liquid below the upper solidified layer forms internal shrinkage. The nature of inside surface of shrinkage changes with type of power supply (AC or DC). The AC treated samples (Fig. 4c–e) shows smooth surface, which indicates entrapment of dissolved gas. It may be concluded that the dissolved gas diffuses to the shrinkage zone of the casting. It is observed that increased ECT increases heat input due to Joules heating (\( F^R \)) [21] and increases solidification time and gas entrapment [11-13]. So, the volume of shrinkage cavity increases at increased current.

4.2. Study on castings made in closed (Cope and Drag) sand moulds

Based on the previous observations, this study is limited to melt treatment with AC. Fig. 1 shows that SSM by ECT is also possible in closed sand moulds. It is observed that the ECT is effective as long as the metal remains at its semi-solid state [10-13]. Castings made in closed sand mould are the typical examples of optimum use of electric energy. The circuit completes when the liquid metal touches both top and bottom electrodes connected to power supply. It is automatically disconnected due to contraction of solid casting. Therefore, there is no need to switch on and off electric current in individual mould. The untreated sample (No 1, Fig. 6a) contains both gas porosity and internal shrinkage located at the central zone “A” of the casting section. This is a common phenomenon in normal castings; however, these
defects are minimized at 2A AC treatment (sample 4, Fig. 6b). This is due to the optimized fluid flow (by ECT/ EHD) [7-9] that fills up the interdendritic areas during solidification. Secondly, this process removes the dissolved gas also. Further increase of current increases the intensity of fluid flow [7-9], as well as, heat input (I²R) to the molten metal [19]. This heat input increases the solidification time [11-13] and dissolved gas. Therefore, the dissolved gas (Sample 6, Fig. 6c) cannot be removed at higher intensity ECT. Fig. 6c shows that the gas porosity is aligned parallel along the current flow direction [10] indicating that the entrapped hydrogen gas is a part of fluid flow during solidification. The hydrogen is not separated from the melt to form shrinkage cavity in casting. It is obvious that (i) 2A AC is the optimum current for these casting and (ii) maximum utilization of electric energy is possible in closed sand mould.

4.3. Study on hollow cylindrical castings
ECT (AC) is also conducted on hollow cylindrical castings (Fig. 2). The shrinkage profile at the top of the untreated casting (No 0; Fig. 7) shows that the extent of shrinkage at the outer side of the casting is less compared to the inner (or core) side of the casting. This may be explained as during solidification, the solidified layer forms along the surfaces adjacent to the mould/core walls. In untreated casting (Fig. 2b), due to contraction, the outer surface of the casting gets detached from mould wall. However, the inner surface of the casting adheres to the core. Therefore, the heat transfer rate from the outer surface of the casting is reduced compared to the inner surface of the casting. So, the inner wall side of sample shows more shrinkage compared to its outer side.

The shrinkage profiles of the top part of ECT castings are shown in Fig. 7 (No. 2 – 6). It is similar on both sides of each casting. This indicates that during solidification, the solidified layers are detached from both mould and core walls. A comparison between Fig. 8 and 9 reveals this phenomenon. In untreated casting, the outer surface of the casting (Fig. 8b) is free from sand sticking compared to the inner surface of the casting (Fig. 8a). However, the inner side of current treated sample (Fig. 9) is free from sand sticking. This may be explained with the schematic diagram (Fig. 13). In conventional solidification (Fig. 13b), the solidification starts from both the bottom and along the sidewall of the mould. The electric current treatment changes the location of solidification front (Fig. 13c). These phenomena may be explained as the current flow induces both normal and tangential forces at the mould-melt interface [7-9]. The solidified metal layer along mould walls is washed away and comes in contact with liquid pool [3-6]. The nuclei are partially remelt in contact with hot metal before they deposit on the solidification front i.e. at the bottom due to increased density of solidified metal (Fig. 13c). Liao et al [19] reported similar phenomena. Thus the solidification front moves along the vertical direction.

Sample 5 shows typical bands on casting surface (Fig. 10) but these are not observed in untreated and low intensity AC treated samples. This may be explained as the effect of deposition of coarse grain at the solid liquid interface. It is observed [11–13] that current treatment beyond a critical limit increases
solidification time and the grain size. The electric energy increases heat input as \( I^2 \times R \) [21]; \( I = \) current and \( R = \) resistance of molten bath. This additional heat takes longer time to dissipate and causes grain coarsening. Those coarse grains settle at the bottom i.e., at the solidification front. This layer contracts after freezing. Meanwhile, another layer is started forming just above the solidified layer that causes band formation (Fig. 13c). To summarise, (i) the current treatment changes the movement of solidification front along vertical direction only (ii) the metal mould reaction is reduced due to detachment of solidified metal from mould walls, (iii) due to formation of coarse grains at higher treatment current, typical bands appears on the casting surface.

4.4. Gas porosity
Another effect of ECT is the removal of dissolved Hydrogen from molten Al-alloy. Fig. 11 (a-e) shows the variation of gas porosity in castings treated with increased current intensity. Naturally, porosity is the maximum for untreated sample (Fig. 11a) but it is significantly reduced by low intensity AC (Fig. 11b). Ahmed et al [16-17] mentioned that flow of current through molten metal creates a condition similar to “cold plasma” where both electrons and positive ions take part in transfer of electrical charge [18]. In this process, \( H \) in melt forms \( H^+ \) ions and transported from the zone of higher metallostatic pressure to lower metallostatic pressure and escapes to the atmosphere [12-13]. On the contrary, gas content in casting gradually increases with increased current beyond a critical current (Figs. 11c - e). Similar phenomenon is also reported in the other studies [11-13]. The reason is that increased current flows through melt increases fluid flow [7-9], as well as, heat input to the melt and therefore increases solidification time[12,13,21] that causes gas entrapment.

4.5. Optical microstructures
Fig. 12(a-c) shows optical microstructures of samples without and with ECT. The untreated sample (Fig. 12a) shows coarse dendrites of primary \( \alpha \)-phase. Low intensity current (2A AC) treatment changes the microstructures to a mixture of fragmented dendrites/ globular primary phase. However, increased current (sample 3, Fig. 12c) increases volume fraction and size of the globular \( \alpha \)-phase compared to sample 2. It is observed that microstructures developed by EMS [4] and Rheo-processing [20] routes are very much similar to microstructures of ECT samples (Fig. 12b & c).

4.6. Energy consumption
It is observed from the Table I that the specific energy consumption is minimum for electric current treatment compared to electromagnetic stirring [4] or mechanical stirring [22-23] methods. This indicates the energy conversion efficiency is significantly high in ECT compared to LEMS or mechanical stirring. In ECT [10-15] /Plasma [16-19] / EHD [7-9] the electric energy is directly converted to kinetic energy to move charged ions or electrons in liquid metal. However, in LEMS /RMS [3-6] the electric energy is first converted to magnetic energy which then converted to kinetic energy to stir liquid metal. Therefore, ECT is an energy saving process compared to LEMS/ RMS or mechanical stirring.

5. Conclusions
1. At an optimum intensity, (50 Hz AC) electric current treatment (ECT) eliminates internal shrinkage incastings, however, it increases with increased current.
2. AC treatment is more effective compared to DC treatment.
3. Treatment with increased AC current increases gas porosity.
4. DC treatment causes interdendritic shrinkage formation but AC treatment favours gas entrapment at thecasting sections.
5. Optimum utilisation of energy is possible during ECT in closed box sand casting.
6. During casting by ECT, the solidification front moves along vertical direction
7. ECT reduces metal-mould reactions.
8. There is a good similarity between optical microstructures of ECT samples and conventional
SSM samples.
9. At increased ECT, typical casting bands are observed on casting surface due to formation of coarse grains.
10. ECT is more energy efficient compared to compared to LEMS / REMS.

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