Pulse electromagnetic force microstructural control at continuous billet casting 7xxx Al-alloys

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Abstract

In this study, the original equipment and methods for the macro/microstructure managed formation in the crystallizers of continuous casting processes by the applying of the amplitude modulated (AM) pulsing magnetic fields (PMF) it the electromagnetic stirrer (EMS) has been developed and tested.

Method has provide the complex electrodynamic, hydrodynamic and acoustic pulse-force processing of unsolidified casting product portion for providing equalizing of solidification front in the billet mushy zone. Resulted non-dendritic type of microstructure has been provide by the means applying: Pulse magnetic field with periodically changing in time amplitude (AM-PMF); Pulse amplitude-modulated rotating melt stirring (AM-PRMF); Pulse amplitude-modulated 3D-helicoidally rotating melt stirring.

Study efficiency applying of unidirectional axial pulse magnetic field (AM-PMF) with pulse frequency in range 5~15Hz, carried frequency in range 22~55Hz, at intensity of MF 0.05~0.1T, for semi-continuous 7xxx alloys (analogue 7075 alloy) 7'billet casting on micro- and macrostructure billet formation has been show reaching the stabile effect for non-dendrite state microstructure formation in all billet cross-section. As well-achieved uniform and homogeneity microstructure state with average grain size not more 100μm, and for middle and central billet part in range 60~80μm, in 3~5 times lowest instead grain sizes 200~650μm at DC casting without EMS, or instead 150μm grain sizes as for conventional rotating EMS. As well, fully solved problems of axial and structural segregation, hot-crack ability or micro-cracks on grains edges and micro-porosity occurring.

Key words: High-strength aluminum alloys, continuous billet casting, electromagnetic stirring, pulse magnetic field, microstructure, grain size

Introduction

As known at the continuous casting of the billets from the 6xxx or 7xxx series high-strength aluminum alloys are very important to provide the special hydrodynamic, temperature and heat-force impact conditions, that there are playing leading role at the macro- and microstructure formation at the billet solidification [1]. It has comprised in the creation of the required conditions of the solid melt skin formation at the water-cooled crystallizer walls, at that to provide high intensity cooling of the solidifying billet, included removing heat from the melt volume in the full relationships with the billet pulling speed at the continuous casting process.

Depend from the billet size 2~10 inches the formation equiaxial by billet cross-section of microstructure are so very important problem [1, 2]. Solution of the dispersed fine microstructure in the all billet cross section are comprised in the creation into liquid state alloy in crystallizer the special 2D~3D contactless melt stirring for creation small different by the temperature and chemical compositions of liquid phase behind front of solidification [1, 2]. This effect can achieved through the conversion of the solidification front surface of billet mushy zone from crater/parabolic type into a smoothed linear, flat front. As well, no less important role of the electromagnetic melt stirring play the force hydrodynamic interaction in the mush zone [1, 3], where are melt take the semi-solid state.

As known at the continuous casting from 7xxx-series of high-strength wrought aluminum alloys on today widely apply electromagnetic stirrer (EMS) by the AC electromagnetic fields for the creation into melt of electromagnetic forces for melt stirring. Most applied for that it is rotating, traveling or combined electromagnetic fields, that using in the 3-phase's electromagnetic stirrers of radial, running (linear) or combined constructive executing.

However, at the applying contactless melt stirring so much important the electric current shape and mode, that in result are predict mode and direction intermixing, as well melt speed stirring, which also have some limitation. The last interesting trend in the EMS scientific researches take placing into creation of the pulse mode impact to the melt into continuous casting crystallizers by the changing in time magnetic field intensity, with different frequency, amplitude and shapes of pulses, using poly-harmonic AC, modulated by amplitude, frequency, phases and et.

Developing method and device for pulse EM-force microstructural control at continuous billet casting 7xxx alloy

Conceptual approach for the creation improved special regimes (modes) of 3D-microturbulent's submerged electromagnetic melt stirring for EMS-crystallizer conclude in creation of pulse magnetic fields/forces, at using amplitude modulation 3-phase's AC-magnetic fields with modulation ratio (M), frequency (f), magnetic intensity (B).

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For practical researching in this study has selected for three main modes: - Pulse magnetic field with periodically changing in time amplitude (AM-PMF); - Pulse amplitude-modulated rotating melt stirring (AM-PRMF); - Pulse amplitude-modulated 3D-helicoidally rotating melt stirring.
In contrast to existed 3-phase's usually applying radial 3~9 poles EMS devices, there are original design of 3-phases's EMS-mold (fig. 1, 3), comprised: vertical water-cooling round short crystallizer (150~225 mm length); 6-poles EMS electromagnetic system, contained by three individual, mechanically and electrically divided each by one, C-shaped 2-poles electromagnets. Each one of it are located in perpendicular to longitude axes of crystallizer under angle 120° (180° or 90° accordingly for double or fourth EM-system design) has been developed and tested (fig. 1~3).

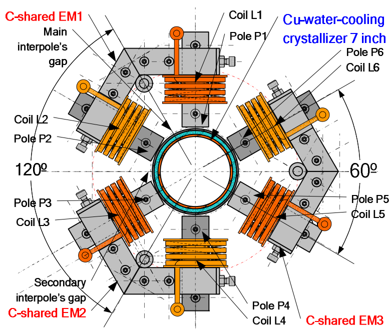


Fig. 1. Scheme of 6-pole's EMS device for electromagnetic stirring.

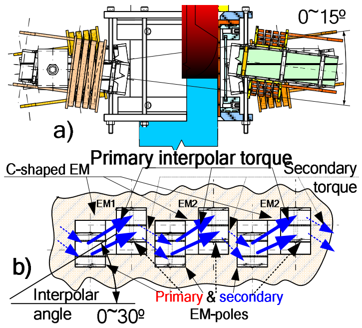


Fig. 2. Tilting EMS-poles (a) and its spatial distribution (b) at helicoidally torque.

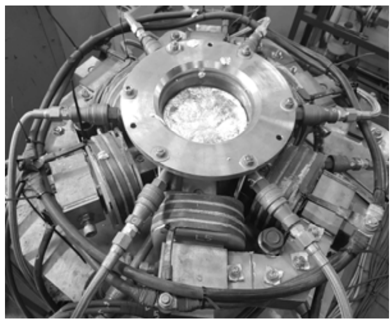


Fig. 3. Prototype of 3-parts 6-poles EMS in AM-PRMF testing mode.

Each one C-shaped electromagnet (fig. 1) consisted from main C-type magnetic core, placed around crystallizer and have by two pole's, adjustable by lengths and vertical tilting angles between each other (±0~15°), relative to the horizontal plane (fig. 2 a, b). Each nearby located poles has directed perpendicularly to longitude axes of crystallizer (billet) with angle between each for 60°, optionally.
Unlike to existed on today methods at creation poly-harmonic AC-magnetic fields for EMS, comprising amplitude modulated mode, in present development has applied method of algebraic superposition of two harmonic magnetic fields $B_{1n}\sin(\omega_{1n}t+\varphi_1)$, $B_{2n}\sin(\omega_{2n}t+\varphi_2)$, with different intensity ($B_{1n}\neq B_{2n}$) and frequency ($f_{1n}\neq f_{2n}$). Each one magnetic fields $B_{1n}(t)$ and $B_{2n}(t)$ generating by the two nearest located electromagnetic poles (P1n and P2n) in its inter-poles gaps for each C_n-shaped electromagnet, at the supplying it's coils (L_{1n}, L_{2n}) by the AC currents (I_{1n}, I_{2n}) with different frequencies and voltages (U_{1n}, U_{2nn}). For that the special EMS-power supply unit, consisting as minimum two electrically divided 3-phases AC power supplying channels (Ch1, Ch2), with adjustable and controlled voltages (U_1, U_2), frequency (f_1, f_2) and current (I_1, I_2), based on the standard frequency inverters (0.1~400Hz) has been developed.
The pulse magnetic field with periodically changing in time amplitude (AM-PMF) mode has been create at the supplying EMS-coils (L1, L3, L5), connected by star and located on left's poles each C-shaped electromagnets, and coils (L2, L4, L5), are placed on it right poles, by the harmonic AC-electrical currents $I_1(t)=I_1\sin(2\pi f_1 t)$ and $I_2(t)=I_2\sin(2\pi f_2 t)$. Each AC has different frequency ($f_1\neq f_2$, but $f_1<f_2$) but equal value for magnetic flux intensity $B_{1n}=B_{2n}=(U_n/f_n)$. At the its interaction in the C-shaped electromagnet inter-poles gap, and also in the gap between nearby located second and third C-shaped electromagnets (fig. 2b), has been created amplitude-modulated magnetic field $B_{AM}(t)$ (fig. 4a), as a result superposition of two magnetic fields $B_{1n}\sin(2\pi f_{1n}t+\varphi_1)$, $B_{2n}\sin(2\pi f_{2n}t+\varphi_2)$ with different frequencies (1).

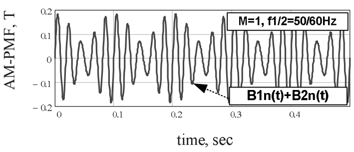
$$B_{AM}(t) = B_{1n}\sin(2\pi f_{1n}t)+B_{2n}\sin(2\pi f_{2n}t) = 2B[\sin(2\pi\{f_{1n}+f_{2n}\}t)\times\cos(2\pi\{f_{1n}-f_{2n}\}t)] \qquad (1)$$

Wherein shape, frequency and amplitude dedicated by the result of the algebraic product of two main harmonic component, with summed frequency $\sin(2\pi\{f_{1n}+f_{2n}\}t)$, - carrier frequency, and difference $\cos(2\pi\{f_{1n}-f_{2n}\}t)$ - envelope.
At the interaction resulted pulse magnetic field $B_{AM}(t)$ (fig. 4a) with the unsolidified casting product portion (liquid molten metal) in crystallizer, there are create the pulse amplitude modulated electromagnetic force (fig. 4b) by the Lenz's law, that are directed from around side to the ingot center in horizontal plane (fig. 5a, b), presented as (2).

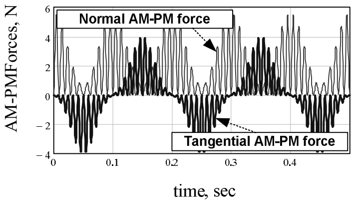
$$F_{AM}(t) \approx kB_{AM}\,(1 - 0.5\cos(4\pi f_{1n}t) - 0.5\cos(4\pi f_{2n}t) - \cos(2\pi\{f_{1n} - f_{2n}\}t) + \cos(2\pi\{f_{1n} + f_{2n}\}t) \qquad (2)$$

Pulse magnetic force $F_{AM}(t)$ (2) have an 5 components: 1) "1" constant component, that are create EM-pressure, providing reducing friction effect of billet with wall; 2) and 3) $0.5\cos(4\pi f_{1n}t)$, $0.5\cos(4\pi f_{2n}t)$ - as two half-amplitude double frequency vibratory components, accordingly for the summing harmonic magnetic fields B_{1n}, B_{2n};

4) $\cos(2\pi\{f_{1n} + f_{2n}\}t)$ - vibratory component with summed frequency and 5) $\cos(2\pi\{f_{1n} - f_{2n}\}t)$ - vibratory component with difference frequency, predicted shape, waveform and frequency of the electromagnetic force pulsation, - named as an modulation frequency. On fig. 4b an illustrated time diagram of influencing modulated by amplitude resulted electromagnetic force divided on normal and tangential components, for conditions f_1=50Hz, f_2=60Hz, M=1, B_{AM}<0.1T.

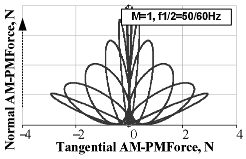


a) AMPM field, Δf=10Hz, M=1



b) AM-PM force

Fig. 4: Time diagrams AM-PM field (a) and normal and tangential components of resulted AM-PM forces (b).



a) 2D-interpole PEMF

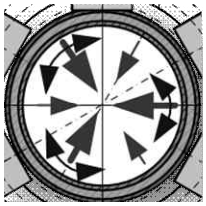
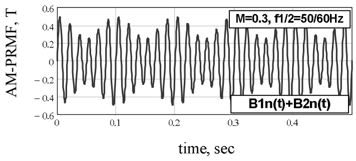
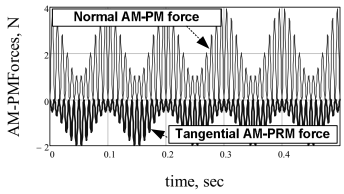

b)

Fig. 5: 2D-diagram impact direction for AM-PM force (a) and axial/radial melt stirring in crystallizer (b).

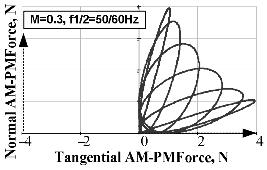


a) AMPRM field, Δf=10Hz, M=0.3



b) AMPM force

Fig. 6: Time diagrams AM-RPM field (a) and normal and tangential components of resulted AM-PM forces (b).



a) 2D-interpole PREMF

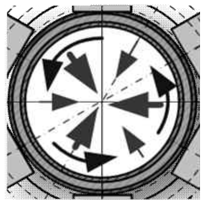

b)

Fig. 7: 2D-diagram impact direction for AM-RPM force (a) and axial/radial melt stirring in crystallizer (b).

5th of low frequency vibratory component (2) predict the main pulsation force hydrodynamic impact on the melt into crystallizer, and have perpendicularly direction to it center (fig. 5). As well, at the using two magnetic fields with different frequencies but equal intensity, summed interaction describing as periodical in time mode, when at the coincidence its phases – electromagnet working in the opposite mode, and after (πn) time transferring to the agreed mode (fig. 4b, 5a,b), that to explaining of tangential shaking stirring mode for case AM-PM forces with M=1.

For creation pulse amplitude-modulated rotating melt stirring (AM-PRMF) fig. 6~7, at combination axial pulse and radial pulse rotation stirring mode realizing at not equal value of the magnetic flux intensity $B_{1n} < B_{2n}$ and $M = B_{1n}/B_{2n}$= 0.7~0.3. In this case creating component of the amplitude-modulated pulse magnetic forces (AM-PM force), directed from around to ingot center and component of running (pulse rotating magnetic field) (fig. 7a). Resulted magnetic field (fig. 6. a) having additional tangential component's - $(B_{1n} - B_{2n})\sin(2\pi f_{1n}t)$ (see fig. 6b – blue colored line), activated of pulse rotation magnetic field (PRMF), (fig. 7) in the direction dedicated by the shift angles of the 3-phase electric current feeding coils L1, L3, L5 of EMS. As well, one from both summing harmonic fields, having an higher intensity (0.15T and 0.05T accordingly), also including that using 3-phase electric current, the higher components are creating the rotary torque, that are presented on fig. 7 as tangential component.

In additions, at adjusting of vertical tilting angles (±0~15°) for both poles of the C-shaped electromagnets (fig. 2), there are providing creation of tilted up rotation torque at pulse stirring mode. Additional AM-PRM forces having an vertical components have creating as minimum 3 (three), arranged around crystallizer pulse rotary torque with vertical (up stronger and down smaller), at performing helicoidally pulse rotary melt stirring mode into crystallizer.

Experimental evaluation microstructural control by pulse magnetic field for 7xxx alloys billet casting

Experimental researches efficiency applying of pulse magnetic field with periodically changing in time amplitude for providing the similar by grain size of micro- and macrostructure in the central, middle and surface billet parts as tested alloy was selected analog of the 7075 wrought aluminum alloy at it semi-continuous billet casting with 7inch diameter.

As a main vessel was used water-cooling coper cylinder crystallizer, having lengths 225 mm and internal diameter 185 mm. In the bottom side for the starting billet pulling process at first time was attached the starting head, further move down with managed speed. For the temperature range 7075 alloy 690~710°C accordingly to the cooling rate facilities of crystallizer 7inch billet pulling speed has been applied in range 60~80 mm/min.

For study of AM-EMS processing efficiency has been produced 3-types billets: 1st - DC casting process (fig. 8 a, b); 2nd - with applying pulse amplitude modulated electromagnetic unidirectional processing 10 Hz oscillation and carried frequency 55Hz (fig. 8 c, d), at the supplying electromagnetic coils of EMS by 60Hz and 50Hz electric current with equal magnetic field intensity. As 3rd mode, has been applied the two-components unidirectional pulse and pulse rotation stirring mode at modulation ratio M=0.3. For deeply studying of pulse hydrodynamic and acoustic impact for microstructural processing in researches the 50~60Hz magnetic fields range was selected, wherein on billet depth more 22 mm from crystallizer wall its intensity and electrodynamic impact have reduced in 2 times value.

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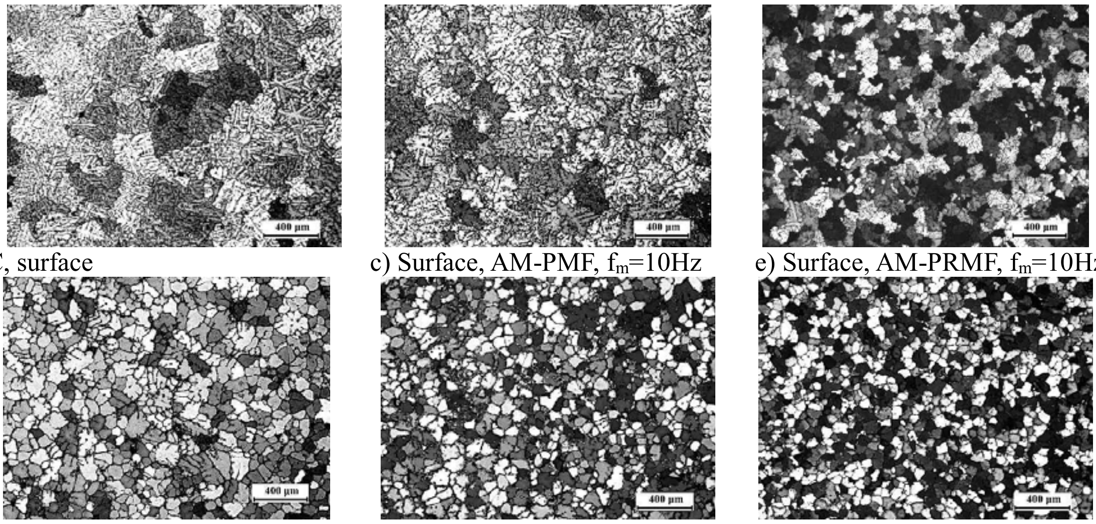

a) DC, surface c) Surface, AM-PMF, f_m=10Hz e) Surface, AM-PRMF, f_m=10Hz

b) DC, midle/center d) Midle/center, AM-PMF, f_m=10Hz f) Midle/center, AM-PRMF, f_m=10Hz

Fig. 8: Microstructure of 7inch billet from 7075 in casting state: - (a, b) DC casting (no EMS); - (c, d) pulse AM electromagnetic unidirectional processing (10 Hz); - (e, f) two-components pulse EM-rotation torque mode (10Hz).

For case DC casting fig. 8a on surface observing large dendrite microstructure with no uniform grain shapes and sizes in ranges 200~650μm. On depths from surface of 40~60mm appear more compact microstructure, similar to the non-dendrite type with characterized sizes of grains 80~250μm (fig. 8b). However microstructure characterized by micro-cracks, that further predicting occurs central macro-cracks, explained by large temperature gradient between surface and central part of billet at it solidification using continuous casting method.

Another picture have case applying pulse amplitude modulated electromagnetic unidirectional processing 10Hz oscillation and carried frequency 55Hz (fig 8 c, d). Surface microstructure characterized as mainly dendrite type (fig. 8c), however more compact with grain 50~300μm, that explained by the pulse force hydrodynamic impact on the front solidification in mushy zone in semi-solid state. But started from 20 mm from billet surface to center (fig. 8d) are presented homogeneity microstructure in non-dendrite state with grain sizes 60~130μm without micro-cracks or micro-porosity.

The more pure and fine structure was obtained for case applying of two components unidirectional pulse amplitude modulated and pulse electromagnetic rotation torque mode processing at 10Hz oscillation and carried frequency 55Hz (fig. 8 e, f). Additional pulse rotation torque in combination with unidirectional pulse impact has provide like more uniform and in 2 time more fine on billet surface microstructure (fig. 8e) grain size less than 150μm, and have view transformation dendrite type to non-dendrite state. Middle and central billet part (fig. 8 e) characterized as non-dendrite uniform and homogeneity state with grain size lowest 100μm, with no evident any cracks or porosity.

Conclusion

The original equipment and methods for the macro/microstructure managed formation in the crystallizers of continuous casting processes by the applying of the amplitude modulated (AM) pulsing magnetic fields (PMF) it the radial EMS has been developed and tested. Method of complex electrodynamic, hydrodynamic and acoustic pulse-force processing provide equalizing solidification front in the billet mushy zone. Study efficiency of unidirectional axial pulse magnetic field (AM-PMF) with pulse frequency 5~15Hz, carried frequency 50~57Hz, at intensity of MF 0.05~0.1T, for semi-continuous 7xxx alloys (analogue 7075 alloy) 7inches billet casting has been show reaching the stabile effect for non-dendrite microstructure formation in all billet cross-section. Two components EMS-processing by unidirectional AM-pulse and pulse electromagnetic rotation torque mode at 10Hz oscillation to provide uniform and homogeneity billet microstructure with average grain size not more 100μm, and for middle/central billet part 60~80μm, in 3~5 times lowest instead 200~650μm at DC casting, or instead 150μm for conventional rotating EMS. Fully solved problems of axial and structural segregation, hot-crack ability or micro-cracks and porosity occurring.

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