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Influence of Combined Vibration with Cavitation and Electromagnetic Impact on the Cast Aluminium Alloy Grain Refining

O. M. Smirnov, Yu. P. Skorobagatko, M. S. Goryuk, M. M. Voron,
A. Yu. Semenko, D. I. Hoida, and S. V. Semiryagin[*]

Physico-Technological Institute of Metals and Alloys, NAS of Ukraine,
34/1 Academician Vernadsky Blvd.,
UA-03142 Kyiv, Ukraine
[*]*LTD Scientific and Manufacturing Enterprise 'Dniproenergostal',*
6 Ehkspresivs'ka Str.,
UA-69008 Zaporizhzhya, Ukraine

Recently, special attention is paid to methods of liquid-metal treatment, which are associated with the action of external physical factors. Thus, an essential role belongs to external energy impacted into the melt. This leads to stabilization and homogenization of liquid state and internal structure as well as its individual components. At the same time, the maximum structure and mechanical properties' improvements of alloys and finished products are achieved in the case of complex processing combining deep refining of melt from harmful impurities (using reagent or vacuum treatment, *etc.*) with a physical effect on solid-state microgroups in liquid metal. Various technological methods for imposing dynamic effects during pouring and solidification are become widespread to suppress and prevent defects during production process. Particularly high efficiency of dynamic effects is achieved by simultaneous application of vibration pulses to the melt and regulated forced stirring. The study is based on the idea of using the linear pinch-effect phenomenon to influence its thermal and force factors on aluminium melt during its repeated circulation pumping through a local zone with a pressure reduced relative to atmospheric one.

Corresponding author: Yuliya Petrivna Skorobagatko
E-mail: yulka.ukr@gmail.com

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Key words: melt treatment, physical fields, vibration, pinch effect.

Останнім часом особливу увагу приділяють тим способам впливу на рідкіснометалеві середовища, які пов’язані з дією зовнішніх фізичних чинників. Істотну роль відіграє зовнішня енергія, яка вводиться у металевий розтоп, що приводить до стабілізації та гомогенізації його рідкого стану та структури загалом, а також її окремих складових. Максимальне поліпшення структури та підвищення механічних властивостей стопів і виробів з них досягається у разі комплексного оброблення — комбінування глибокого рафінування розтопу від шкідливих домішок (з використанням реаґентного оброблення, вакуумування тощо) з фізичним впливом на мікроугруповання в рідкому металі. У процесі виробництва заготовок для придушення та запобігання дефектам набули поширення різні технологічні прийоми накладання динамічних впливів у процесі заливання та затвердіння. Особливо висока ефективність динамічних впливів досягається у разі накладання на розтоп вібраційних імпульсів разом із реґламентованим примусовим перемішуванням. В основу дослідження закладено ідею використання явища лінійного пінч-ефекту для впливу його теплових і силових чинників на алюмінійовий розтоп під час його багаторазового циркуляційного прокачування через локальну зону із пониженим щодо атмосферного тиском.

Ключові слова: оброблення розтопу, фізичні поля, вібрація, пінч-ефект.

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1. INTRODUCTION

Application of physical fields has a thermal and force effect on the liquid alloy both at the macrolevel (heating, mixing, transportation, shaping) and at the microlevel (impact on structural inhomogeneities, liquid and solid inclusions, individual components of the alloy). The type of input energy can be different: thermal, mechanical, acoustic, electrical, electromagnetic. Its means, that the main control factor and its effect may be different.

In general, the scheme of metal-melts’ physical treatment can be represented as it is shown in Fig. 1. Regardless to the type of energy introduced into the melt, its source (generator) may be generally introduced like electrotechnological device (ETD) that supplies electrical energy to the converter device. It forms desirable type of energy, which provides a given power of its flow and directly introduces it into the melt. Such a converter device can be replaceable and have various modifications depending on the specific processing goals.

During this treatment, the energy introduced into the melt is distributed as it is shown in Fig. 2. Ideally, an attempt is made to design a system for physical treatment in such a way as to, firstly, minimize the energy losses in the ETD ((W_{lps}, W_{letd}, W_{ldin}) $\to 0$), secondly, to increase

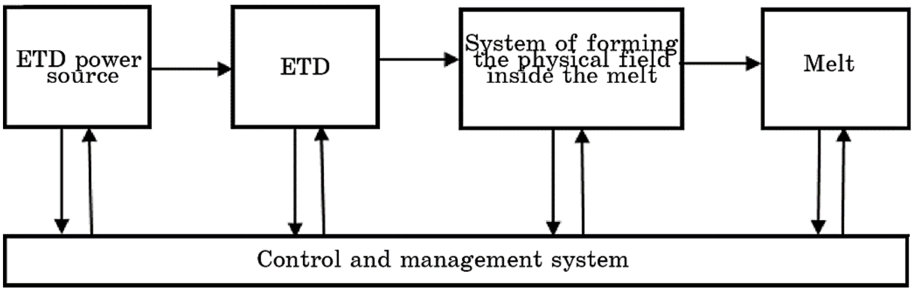

Fig. 1. General scheme of melt processing by physical fields.

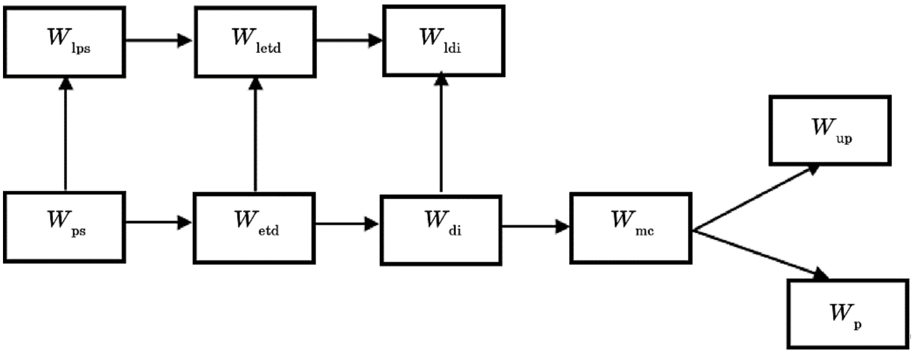

Fig. 2. Redistribution of energy during melt processing physical fields according to the scheme of Fig. 1: W_{ps} is energy consumed by the power supply of the ETD, W_{lps} is energy losses in power supply of the ETD, W_{etd} is the energy consumed by the ETD itself, W_{letd} is energy losses in ETD, W_{di} is energy consumed by the system of direct impact on the melt itself, W_{ldi} is energy losses in a system of melt impact, W_{mc} is the energy consumed by the melt, W_p is productively expended energy in melt, W_{up} is unproductively expended energy in melt.

the efficiency of energy transfer to the melt, and thirdly, to minimize energy losses in the melt itself ($W_{up} \to 0$).

In practical plane, the design of specific devices and the redistribution of energy in them can vary greatly due to the wide variety of energy types used in processing. Thus, it is easiest way to conduct mechanical energy (rotation, vibration) into the melt. However, the most concentrated and powerful release of energy in the volume of liquid metal can be achieved when acoustic shock waves are created in it, including cavitation achievement. At the same time, the maximum completeness of energy transfer to the melt occurs when using electric and electromagnetic fields.

The main methods of dynamic impact on the melt can be conditionally divided into two main groups: vibroimpulse and electromagnetic impacts. These techniques usually provide an active effect on not only heat and mass transfer in the liquid phase, but also may cause significant changes in processes inside the two-phase zone. In many cases, they also may effectively affect the macro- and microstructure of castings.

It is necessary to answer a certain set of questions in order to achieve the maximum positive effect of treatment: a) what energy indicators of stirring process are the most rational, b) treating source application position, c) what volume of the melt must be stirred (the entire volume or a local area), d) preferred flow movement (linear or circulation), e) to what extent the reconstruction of the existing process equipment is required when implementing the proposed stirring scheme.

The idea of vibroimpulse action application on melt can be implemented in various ways. The choice of the method of applying the impact, apparently, is determined by the specifics of each existing object, as well as the goals that are solved during processing. In general case, vibroimpulse action can be applied either to the casting mould, or directly introduced into the melt using special devices and pulsators.

The application of vibroimpulse action directly to the casting mould has very significant practical interest, since in this case it is possible to process several castings simultaneously [1–4]. However, the processing intensity may have certain limitations, which are associated, for example, with the strength of the mould. There is also no unambiguous opinion in the literature, which of the vibration directions (horizontal, vertical, or reverse–rotational ones) should be preferred. Probably, to answer this question, additional development of vibroimpulse action in direct relation to specific objects and types of suppressed defects theory is required.

The nucleation of crystals begins symmetrically from the source of vibrations in the regions adjacent simultaneously to the solidifying shell and the free surface of the melt. The process has an avalanche-like character, and finely dispersed crystals fill the entire space of a liquid metal volume. A certain disadvantage of this processing method is the stirring inhomogeneity of the liquid volume. The principal diagram of molten metal pulsating action method (Fig. 3) includes periodic filling and displacement of metal from a ceramic tube immersed in the melt.

Metal level fluctuations in a pipe are achieved by a certain change in the gas pressure in its internal cavity. While treatment of a liquid bath is provided, a ceramic pipe is placed in its central part [5]. In this case, high efficiency of the impact is achieved in a resonant mode of pulsations. Accurately saying, it happens, when the frequency of pulsations coincides with the natural frequency of oscillations in the ladle-dip pipe system. The pipe immersion depth is usually 0.25–0.50 of the liquid bath height, and the pulsation frequency is 0.25–4.0 Hz. The di-

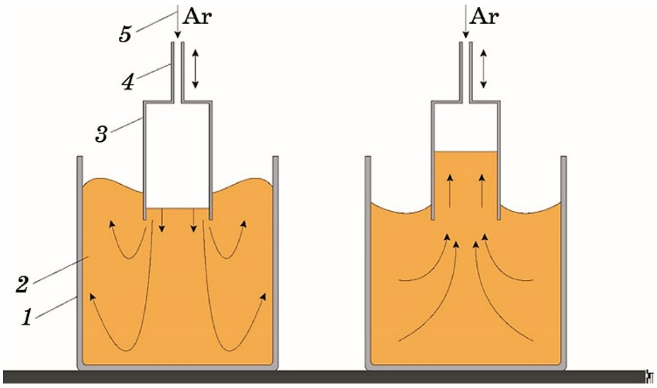

Fig. 3. Scheme of the method of pulsating action of molten metal: *1* is vessel body, *2* is liquid metal bath, *3* is pulsator, *4* is branch pipe for supplying argon, *5* is argon.

rected cyclic motion of the displaced metal jet significantly changes the direction and velocity of the flows in the liquid bath [6–8]. In addition, vibrations of sufficiently high intensity are superimposed on the melt during processing.

Among the most important physical effects, the occurrence of which is caused by the vibration and pulsation effects superposition, the following processes can be attributed: a) phenomenon of cavitation in the volume of the liquid phase, b) phenomena of nucleation and crushing of solid particles inside the melt, c) phenomenon of solid phase particles growth phase in a supercooled melt.

Usually, under the phenomenon of cavitation, most authors mean the occurrence and disappearance of caverns (closed gas cavities) in a liquid under the influence of certain disturbing factors [9–12]. The process of cavitation effect occurrence and development depends on the initial state of a liquid, including its viscosity and the presence of solid or gaseous impurities in it, as well as on the pressure field in the cavitation zone.

Forces that cause cavities formation and collapse during vibrational cavitation are continuous pressure fluctuations with large amplitude. These vibrations can be created by any surface immersed in a fluid that vibrates in a normal direction and creates pressure waves inside the fluid. Caverns do not form until the oscillation amplitude is not large enough and the pressure does not drop to the saturation vapour pressure or lower [9]. The small cavities formed in the places of discontinuity can pulsate without changing the content of the vapour-gas mixture inside the volume or grow intensively due to the action of tensile stresses of vibrational waves or begin to close (collapse) under the action of vibrational waves compressive stresses to generate smallest 'fragments' of bubbles and developing high local pressures near the collapse sites.

The method of electromagnetic stirring has become quite widespread in practice to improve the quality of continuously cast billets and castings obtained by special foundry methods [13–17]. The mixing effect in this case is achieved by applying an electromagnetic field to a melt. At the same time, by adjusting the parameters of the electric current, supplied to electromagnetic coils, located near the surface of the workpiece, it is possible to obtain different speeds and directions of liquid metal flows.

Meanwhile, the tops of the dendrites are remelted or simply mechanically collapsed under the action of the formed metal flows in the liquid bath. In turn, such fragments of dendritic branches become additional crystallization centres and increase the zone of equiaxed crystals. Therefore, forced mixing can stop the process of columnar crystal zone growth and to promote the beginning of the equiaxed crystal zone formation. Stirring of a liquid metal under the solidifying shell of cast billet ensures that the chemical composition of crystallizing metal becomes averaged. Liquid metal flows into the unsolidified part of the workpiece, reducing the size of all retractable dendrites and preventing the formation of bridges between them. Some studies have established that even after almost 50–60% of liquid metal has crystallized, the two-phase mixture has the characteristics of a liquid, which allows it to continue its stirring [15, 16].

Turbulent motion that exists in liquid metal during electromagnetic stirring reduces the tendency for already existing oxide inclusions to settle on the interfacial interface. Directed flow also ensures the erosion of liquates-enriched local volumes of melt. Non-metallic inclusions, formed under such conditions, are smaller and more evenly distributed in an axial zone of crystallizing billet.

In general, electromagnetic stirring improves the quality of the surface and subcrystal zone, and the use of electromagnetic stirring in the internal volumes improves the internal structure of the workpieces and reduces segregation and shrinkage porosity in the central zone. Quality control of ingots and castings with application of electromagnetic stirring application seems to be very problematic, since as the cross-section of the billets increases. It causes problems with ensuring a uniform penetration of electromagnetic field over the entire cross-section. Therefore, it seems promising to carry out electromagnetic processing immediately before pouring into the mould and combining it with other methods of physical influences [18].

2. PHYSICAL MODEL AND RESULTS

The effect of vibration and pulsation on a melt during crystallization should be considered both in terms of forced controlled stirring and in terms of some known effects demonstration. The differentiation of these effects in relation to the molten metal seems to be extremely difficult in technical terms. In general, the main goals of solidification processes under pulsation and vibration exposure physical modelling were defined as a qualitative and comparative quantitative assessment of the solid phase particles growth of nature. It also helps to provide identification of solid phase particles formation sources in melt and the degree of their influence on solidification processes. Accordingly, in terms of formulation, the task of methodology for physical modelling of solidification processes under the imposition of external influences should include the following constituent elements:

a) determination of the working substance, which allows ensuring a correct assessment of solidification processes in accordance with the objectives of the research;

b) substantiation the choice of modelling object and determination of the physical model geometric dimensions in accordance to selected similarity criteria;

c) choice of a physical-quantities' set, that are measured during the simulation and choosing methods for their determination in accordance with the research objectives.

At the first stage, modelling was carried out on ENAW-8176 aluminium alloy (0.03–0.15 Si, 0.4–1.0 Fe, 0.1 Zn (% wt.)). The advantage of this simulation consisted in:

a) a metal is used as a modelling substance, which forms a dendritic macrostructure of various dimensions and dispersity;

b) a model ingot (casting) is cast in bulk form, which makes it possible to maintain similarity when comparing different castings;

c) the use of aluminium alloys as a modelling substance makes it possible to estimate the effect of pulsation and vibration on the change in the macrostructure of ingots with a high degree of accuracy.

The aluminium alloys melt was prepared in a cylindrical graphite crucible, placed in an electric shaft furnace. The alloy during melting was protected from oxidation by a layer of activated carbon. During the experiments, round castings with a weight of 0.9 kg and a height of 0.095 m were obtained. They were poured into a specially prepared sand mould. Such choice is explained, first, by the desire to achieve conformity with the criteria for modelling the conditions of heat removal during solidification. Simultaneously with the experimental castings, comparative castings were obtained without the application of external influence.

Vibration treatment of experimental castings was carried out on a special vibration platform, which was installed on concrete base and was equipped with a mechanical vibrator that modulates sinusoidal oscillations with a frequency of 0.5–70 Hz. The scheme of an experimental shaker for castings treatment is shown in Fig. 4 [19].

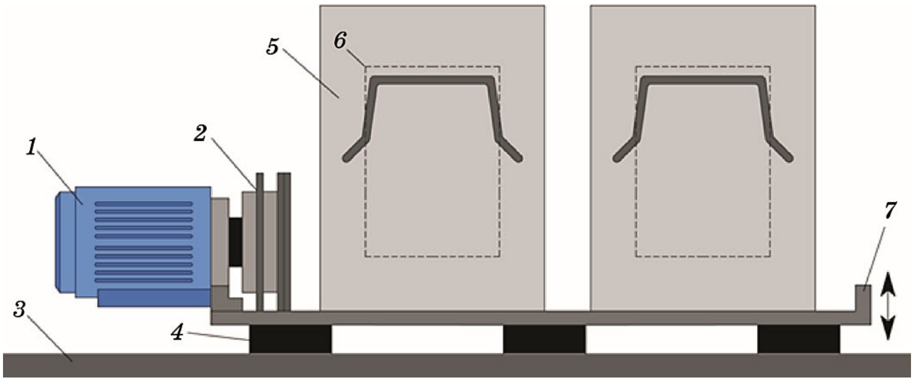

Fig. 4. Scheme of the vibration stand for experimental as-cast parts treatment: *1* is electric engine, *2* is vibrator, *3* is foundation, *4* is elastic pads, *5* is mould box, *6* is casting, *7* is vibrating plate.

Vibration treatment was started before pouring the metal and continued for 280–300 seconds after its completion. Additionally, the amplitude and frequency characteristics were evaluated directly at the edge of casting mould (piezoelectric vibrometer VIP-2). The developed scheme of vibration processing ensures a relatively uniform distribution of vibrations over the entire area of a plate (fluctuations in the measurements amounted to no more than 12%).

Amplitude–frequency range of oscillations was chosen in accordance with the considerations for ensuring the cavitation nucleation regime with more uniform solidification of the whole casting. Considering the high volumetric shrinkage coefficient for aluminium, the efficiency of vibratory treatment can be assessed by the degree of melt settling in the mould. Subsequently, the oscillation frequencies, which ensured the maximum melt compotation, were taken as the base ones for obtaining experimental castings.

3. SIMULATION AND CAVITATION EFFECT

Under the phenomenon of cavitation, most researchers mean the sudden appearance and disappearance of cavities (closed gas cavities) in a liquid under the influence of disturbing factors [9–12]. Cavitation process occurrence and evolvement depends on the state of the liquid, including its viscosity, and the presence of solid or gaseous impurities in it, as well as on the pressure field in the cavitation zone.

The forces that cause formation and collapse of cavities during vibrational cavitation are continuous pressure fluctuations with large amplitude. These oscillations can be produced by any surface immersed in the fluid that vibrates in the normal-oriented direction and creates pressure wave oscillations in the fluid. Caverns do not form until the pulsation amplitude is not large enough and the pressure drops to the saturation vapour pressure or lower [9]. Small cavities, formed in the places of discontinuity, can pulsate without changing the content of the gas–vapour mixture inside the volume, or grow intensively due to the action of tensile stresses of oscillatory waves. They also may begin to collapse under the action of compressive stresses of oscillatory waves, generating the smallest ‘fragments’ of solid particles and developing large local pressures near the collapse sites.

The oscillation parameters that ensure onset and subsequent evolvement of cavitation phenomena can be estimated in first approximation from the condition that the peak values of liquid pressure in the field of vibrational forces reach zero approaching values [20, 21]. Therefore, when vibrating a liquid together with a container, the expression for condition of cavitation onset phenomena in an ideal liquid has the following form:

$$f^2\alpha \geq g/4\pi^2 \geq 0.25, \tag{1}$$

where f is oscillation frequency (Hz), α is oscillation amplitude (m), g is free fall acceleration (m/s^2), $\pi \cong 3.14$.

The results of vibration impact on the aluminium ingots structure formation are shown in Fig. 5, *a* (without vibration treatment). As can be seen from the results above, significant effect of macrostructure refining is achieved even at relatively low frequencies (5–10 Hz) and under condition, when cavitation limit is exceeded by 15–20% during treatment (Fig. 5, *b*, *c*). A similar effect was obtained, for example, during vibration treatment with a frequency of 40 Hz (Fig. 5, *d*) under conditions of exceeding the cavitation limit by 15%. In addition, it should be noted that vibration treatment in the low-frequency vibration mode, exceeding the cavitation limit by 30–40% (Fig. 5, *f*), was accompanied by serious bursts of melt and discontinuities in the casting body, which should be considered as a negative manifestation of the treatment effect. Meanwhile, when the cavitation limit is not reached, the effect of exposure noticeably decreases (Fig. 5, *e*). The ratio of frequency values and amplitude of oscillations for the cavitation limit rate here and below was determined according to recommendations by J. Campbell [20].

The process of castings’ formation and crystallization under imposition of pulsating effect, in comparison with castings, which crystallize without any external impact, is characterized by several distinct stages [22]:

a) formation of a large number of solid phase small particles in melt at the beginning of solidification process;

b) enlargement (growth) of formed particles and their gradual sedi-

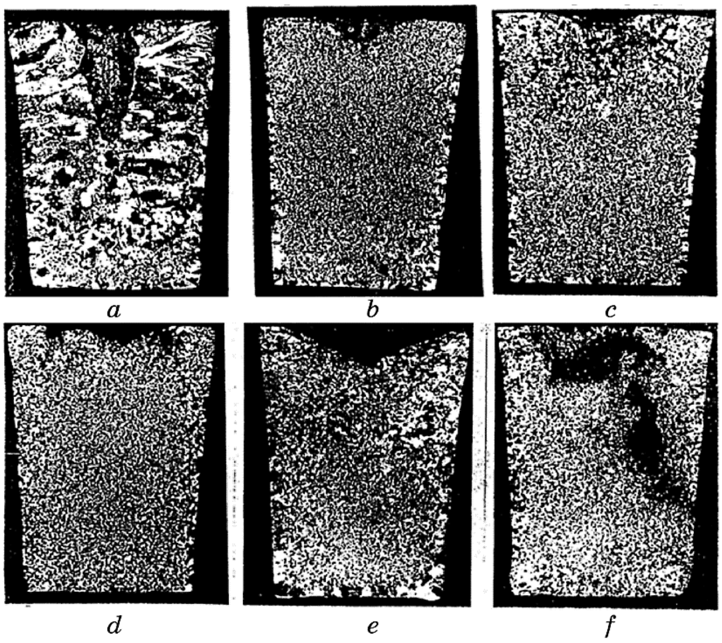

Fig. 5. Macrostructure of experimental aluminium ingots (longitudinal templates).

mentation (to the bottom part);

c) decreasing amount of solid particles in the melt and decreasing the intensity of stirring, resulting in internal cavity overgrowth inside ceramic pulsating tube.

It has been established that varying pulsation treatment modes (pulsation frequency, depth, and diameter of the immersed pipe) leads to significant increase in a rate of solidification front growth in the vertical direction if intensive mixing is provided in the entire volume of the ingots liquid phase of the ingot because of solid particles sedimentation. This roughly corresponds to the resonant regime of pulsations. The maximum rate of solidification front growth in the vertical direction was achieved, when the pipe was immersed in the melt at a level of 0.20–0.30 of the filling height and an inner diameter of 10–15 mm. In this case, almost the entire volume of ingot liquid phase is involved in stirring. With a greater pipe immersion, stirring of the melts upper volumes is significantly reduced. Their involvement in movement mainly depends on the suction mode and the location of pipes lower section.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Discussed results and their connection with the development of vibrational and cavitation phenomena in melt were used in treatment of aluminium melt under conditions of magnetodynamic installation (MDI) using the combined treatment of the pinch effect and local rarefaction. The main condition for obtaining high-quality castings from aluminium alloys is the minimum degree of their contamination with hydrogen and oxide inclusions. In this case, the effect of current channel compression occurs under the action of a magnetic field, induced by the current itself.

In this work, to increase the intensity of the vibroimpulse force action on a liquid metal in magnetodynamic installation, we used the phenomenon of a linear pinch effect, which always takes place in conductors with electric current [23]. Its physical essence lies in the fact that parallel conductors, through which electric current flows in the same direction, attract. While filling the MDI channel, liquid metal can be conventionally represented as a large number of parallel conductors that are attracted to each other. If the current density were the same over the entire cross section of the channel, then, at any point of this section, the force would be directed towards its geometric centre.

It should be specially noted that the pressure due to linear pinch effect is directed from the walls of the cylindrical channel with liquid metal to its axis, while the static pressure, on the contrary, acts on the walls. If the negative term of pressure exceeds the value of metallostatic pressure, the liquid conductor is pinched and ruptures. The electric current, and, consequently, the forces caused by the linear pinch effect, disappear in a broken liquid metal coil. As a result, integrity of coil is restored and the pressure again arises in the metal, caused by the pinch effect and then it breaks again. Thus, in aimed liquid metals, a complex periodic process of rupture and recovery occurs, accompanied by the appearance of an electric arc [24], increase in temperature and pressure pulsation. This effect is realized in closed air-free channels, therefore, a low-pressure region is formed between the metal surface and the channel wall, into which gases dissolved in the melt can diffuse.

To provide treatment of liquid aluminium alloy, based on thermal and electromagnetic influence, a zone of complex action on a melt was created in the central branch of the W-shaped channel inside magnetodynamic installation (Fig. 6) [25]. At the same time, with the help of electromagnetic force, multiple circulations' pumping of liquid metal through the low-pressure zone was provided with initiation in a freely flowing jet inside outlet of the throttling nozzle with effect formation. In this case, the conditions for breaking a determined diameter liquid-metal conductor were provided due to passage of high density alternating electric current through the melt.

As a result, in this zone, the occurrence of electrodynamic oscillations and the cyclic occurrence of electric arc discharges were periodi-

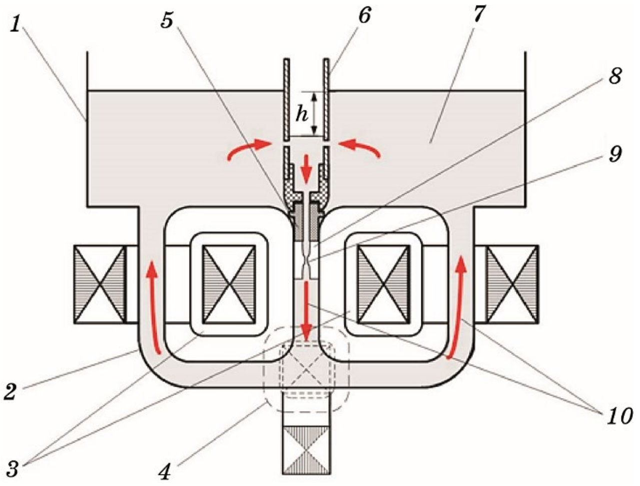

Fig. 6. Scheme of complex processing of aluminium melt in the MDI, when creating rarefaction in the local zone and initiating the pinch effect in a freely flowing metal jet: *1* is crucible, *2* is channel, *3* is inductors, *4* is electromagnet, *5* is replaceable throttling nozzle made of potassium fluorophlogopite (throttle), *6* is metal transporting pipe, that holds nozzle, *7* is aluminium melt, *8* is local rarefaction zone, *9* is region of pinch effect occurrence, *10* is melt circulation direction.

cally observed when a metal jet, which is a liquid metal conductor, breaks. Under the influence of electromagnetic forces, when the installation was switched on a suction mode, metal in a central branch of the channels pipeline was pushed out into the wall side and from them next into the crucible. In this case, the melt from the crucible enters back through the side holes in the metal wire, and then through the hole in the throttling nozzle flows into the central branch of W-shaped channel.

When choosing the value of electric current loads, we proceeded from the currents critical value in aluminium for initiating pinch effect, at which liquid metal conductor would be completely clamped up to its rupture. According to various data [26, 27], this parameter should be in a range 10–25 A/mm^2.

It has been established that 10 mm diameter of nozzles hole corresponded to the optimal modes of complex metal treatment process, since in this case a stable pinch effect was observed. It was accompanied by a complete rupture of the metal jet and the occurrence of an arc discharge in a local zone, located below the throttling constriction (current density of 21 A/mm^2), at a melt flow rate of 0.7–0.8 kg/s through the electromagnetic impact zone. In this case, mass of liquid metal that passed through the treatment zone for 15 minutes was of

600–700 kg (about 7–8 volumes of metal inside the installation). The use of a nozzle with a smaller diameter (5 mm) also made it possible to provide conditions for the stable occurrence of pinch effect and cyclic rupture of the liquid metal conductor with an arc discharge appears directly in the throttling hole (current density is of 80–85 A/mm^2). However, the flow rate of the melt through a treatment zone was no more than 0.2–0.3 kg/s that corresponded to the pumping of only 3 volumes of metal inside installation for 15 min. Increasing nozzle diameter to 15 mm led to a decrease in the current density in the hole cross-section to 10–11 A/mm^2 and the disappearance of the conditions for development of the pinch effect with a break in the liquid metal conductor, both in the nozzle hole and in the zone located below the throttling constriction. In addition, due to an increase in a melts flow rate through the rarefaction zone to 0.9–1.0 kg/s, there was a partial resaturation of the metal with hydrogen and oxide inclusions.

At the same time, presence of two types of pressure oscillations was established: the frequency of oscillations of the first type is of 2.5–3 Hz, the amplitude is of 12–14 kPa, and the oscillations frequency of the second type is of 100 Hz, and the amplitude is of 2–2.5 kPa.

Due to the voltage mismatch in the inductor coil windings, current flow through the liquid aluminium alloy was ensured and pinch effect appeared in the studied local area, as evidenced by a characteristic sound (dry crackling) that appeared with a time interval of 1.5–2.0 s, duration of 0.15–0.25 s and a frequency of 100 Hz. In this case, a regularity, between oscillation packets alternation with a frequency of 100 Hz (at the moment of break) and the time interval between the start of pinch effect was established [28, 29]. The amplitude of second type oscillations was of 2–2.5 kPa.

The periodic occurrence of pulse packets is explained by the alternation of jet rupture processes under the action of electromagnetic forces (during the pinch effect) and the subsequent closing of the electrical circuit, *i.e.*, the periodic restoration of the metal flow from the throttle hole.

The study of oscillatory processes, occurred in the local zone, showed the presence of a force impulse effect on liquid metal passing through this zone. However, it should be noted that the occurrence of pinch effect also causes a local increase of temperature in this region due to the arc discharges when the metal jet breaks.

For providing metallographic studies and mechanical properties evaluations, longitudinal axial templates were cut from the obtained cylindrical aluminium alloy АК7 (A356) castings. It has been established that microstructure of the initial metal (Fig. 7, *a*–*c*) corresponds to the typical structure of Al–Si hypoeutectic alloys (silumin) [30]: a dendritic structure and dotted precipitates up to 1 μm in size inside the grains are observed. Average value of the interaxial distance between

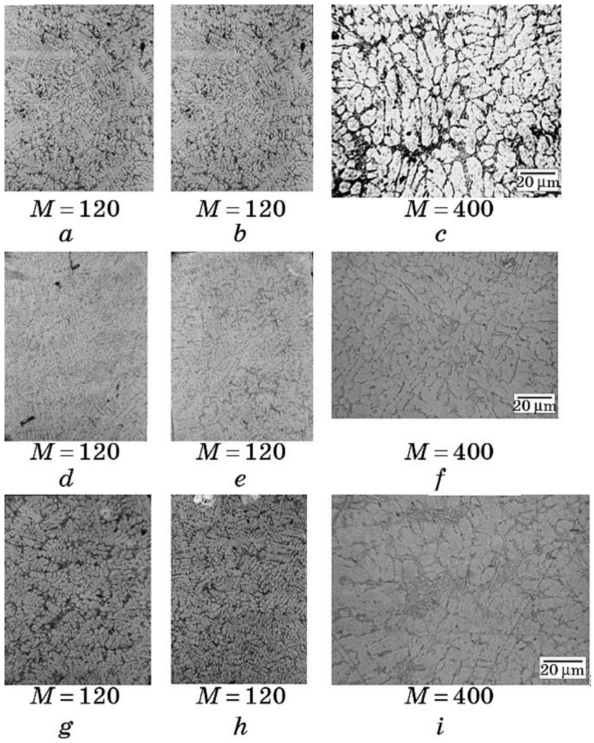

Fig. 7. Microstructure of AK7 (A356) aluminium alloy: the original alloy (*a*–*c*), microstructure of the alloy after 15 minutes complex treatment (*d*–*f*), microstructure of the alloy after 30 minutes of complex treatment (*g*–*i*).

solid solution of aluminium dendrites is within 12.5 μm. The Si grains are fine and round shaped, they are deposited like intergranular eutectic. Silicon accumulations along the grain boundaries may rise up to 18–60 μm.

After 15 minutes of complex melt treatment in the mode of circulation pumping through the zone of local rarefaction and initiation of pinch effect (Fig. 7, *d*–*f*), grains of Al-based solid solution were refined to 7–10 μm. At the same time, Si accumulations located in the original metal decreased in size to 10–15 μm and were evenly distributed, but sharp corners remained. Secondary phase was formed from solid solution, consisting of dark grey inclusions uniformly distributed over the structure in an amount of 1.5%. The size of these inclusions was from 16 to 30 microns, and their skeleton and cheese script-like morphology may correspond to $Al_8Si_6Mg_3Fe$ phase. The results of continuous metal treatment for 30 min are shown in Fig. 7, *g*–*i*. As a result, the grain size of Al-based solid solution decreased to 5–8 μm. Si inclusions have become shorter and more compact. In addition, in the grains of matrix metal, 2–3% of large (less than 20 µm in size) dark secondary inclusions are observed.

Mechanical tests of metal samples showed that elongation index increased up to 3–3.5 times to 2.4% after 15 minutes of treatment. At the same time, tensile strength increased 1.4–1.5 times: from 90 MPa to 125–130 MPa.

After melt treatment for 30 min, a decrease in elongation was noted that amounted to 1.4–1.6%, while maintaining the same level of tensile strength. When treatment duration was 45 minutes, relative elongation decreased to 1.2–1.4% while maintaining the tensile strength at the level of 125–130 MPa.

Metallographic investigations of experimental samples after mechanical tests showed that, due to prolonged treatment for more than 20 minutes, non-metallic inclusions in the form of oxide films are clearly visible on the fractures. Such obstacles significantly reduced mechanical properties of the samples, so to preserve this; it is applicable to filter aluminium during its continuous processing, or to protect the melt from contact with the atmosphere.

It has been established that the complex treatment of liquid aluminium alloy by its repeated circulation through the zone of local rarefaction ensured the removal of hydrogen dissolved in the melt from 0.6 to 0.05 $cm^3/100$ g of metal. An additional heat and electromagnetic force effect, due to the manifestation of the cavitation in connection with pinch effect, promotes the transition of iron from the Al_3Fe phase to the $Al_8Si_6Mg_3Fe$ phase, which is located along solid solution grain boundaries in the form of light grey skeletal plates and contributes to the crushing of primary silicon clusters and the actual structure refining.

Meanwhile, holding metal after treatment for more than 20 min leads to decreasing modification effect, and the amount of hydrogen gradually (for 3–4 hours) returns to its original level. It has been established that the ‘survivability’ of treatment-caused modifying effect is 20–30 min. Therefore, it is advisable to start it immediately before the stage of pouring metal into a mould.

5. CONCLUSIONS

When a vibrational effect is applied to a metal melt, certain conditions are created that cause the occurrence and development of cavitation phenomenon. It depends on the state of liquid, including its viscosity and the presence of solid or gaseous impurities in it, as well as on the pressure field in the cavitation zone. The forces, which cause formation and collapse of cavities during vibrational cavitation, are continuous pressure fluctuations with certain amplitude.

Process of forming castings that solidify when applying a pulsating effect with a frequency of 0.5–2.5 Hz is also accompanied by the manifestation of a cavitation effect with large number of small solid phase fragments formation in a melt at the beginning of the solidification process. Then most of these particles coarsen and gradually sediment. As a result, the macrostructure of the casting becomes refined.

The phenomenon of the linear pinch effect was used to increase the intensity of vibroimpulse action on the liquid metal in the magnetodynamic installation. In this case, a complex periodic process of melt flow rupture and recovery occurs, accompanied by the electric arc, temperature increase and pressure pulsation. This effect is realized in closed airtight channels; therefore, between the metal surface and the channel wall, a low-pressure region is formed, into which dissolved gases may diffuse.

It has been established that in the secondary aluminium alloy AK7 (A356) with a high iron content ($Fe > 1\%$), after 15 minutes of its melt electrophysical treatment, hydrogen concentration decreases from 0.6–0.3 $cm^3/100$ g in original metal to 0.1–0.05 $cm^3/100$ g after treatment. At the same time, the sizes of structural components, including intermetallic compounds, decrease 2–3 times due to the dispersion of microheterogeneities. It is caused by pinch effect in combination with the created forced electromagnetic circulation of the aluminium melt with a flow rate of 0.7–0.8 kg/s through the zone of cyclic local increase in metal temperature (up to 3000 K) and pulsed force action on it.

It is shown that the cyclic electrodynamic and thermal effects on the current-carrying aluminium melt leads to a microstructure refinement of secondary aluminium alloy, as well as to changes of composition and distribution of iron-containing phases. Such effect is reached because pinch effect is initiated in melt flow, as well as the provision of multiple pumping alloy through the complex treatment zone.

It was determined, that after 15 minutes of complex treatment of secondary aluminium alloy AK7 (A356) in MDI (80 kg capacity for aluminium melt), the relative elongation of alloy increased 3 times from 0.8% (original metal) to 2.4% (treated metal). Tensile strength after processing increased 1.5 times. For the used aluminium alloy of the Al–Si system and specific energy consumption of 0.07–0.08 kW/kg, the mass flow rate of the melt through the treatment zone is 0.8 kg/s; the optimal treatment time is 15 minutes.

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