Theoretical and Experimental Evaluation of the Effectiveness of Aluminum Melt Treatment by Physical Methods

V.B. Deev, E.S. Prusov, A.I. Kutsenko

Physical methods of aluminum melts treatment have a number of advantages in comparison with the traditional methods of grain refinement: they do not require the use of expensive additives, they do not influence the change in the alloy chemical composition, and they are more environmentally favorable. Comparative evaluation of various physical methods of aluminum melt processing according to the calculated and experimental values of the solid fraction close to the solidus temperature and the total solidification time on the example of the A356 alloy has been carried out in this paper. It has been shown that when melt is processed by physical methods, the size of the dendritic cell and the structure of the eutectic are significantly reduced. Fluidity of test alloys has increased after the treatment by 18 ... 25% by an average. The most significant increase in the strength characteristics of the A356 alloy has been noted after the combined thermo-temporal treatment of melts and the application of electric current during crystallization (+ 20.5%), as well as thermo-temporal treatment followed by the inert gas purging (+ 20%), herewith more than two-fold increase in ductility has been indicated in each of the above-noted treatment modes.

KEYWORDS: CAST ALUMINUM ALLOYS, GRAIN REFINEMENT, PHYSICAL MELT TREATMENT, FRACTION SOLID, TOTAL SOLIDIFICATION TIME, FLUIDITY, MICROSTRUCTURE, MECHANICAL PROPERTIES

INTRODUCTION

Grain refining treatment is one of the effective ways to control the structure and properties of aluminum alloys. Traditional widely used grain refining additives (titanium, boron, strontium, sodium, phosphorus, etc.) can significantly improve the quality of castings from both hypoeutectic and hypereutectic alloys [1-3]. However, the search for new grain refiners and the development of more efficient methods for grain refinement of aluminum alloys continue to be of interest to metallurgists and casters [4-6]. More and more attention recently has been paid to the development and investigation of methods that make it possible to obtain a refined alloy structure without introducing special additives into the melt. One of the promising ways of ensuring the quality of castings and reducing the material and energy costs for their production is the working out and mastering of advanced methods of melting and casting using physical effects on liquid and crystallizing melt.

Such physical methods as vibrational [7], ultrasonic [8-10], electric [11-13], electromagnetic [14-19], electron beam [20, 21] etc. have been successfully tested for grain refining treatment of aluminum melts so far. At the same time different variants of high-temperature furnace treatment (thermo-temporal treatment, superheat treatment, etc.) are used to homogenize the melt and to refine the grain structure of the castings [22-25]). However, for the industrial production of shaped castings, these technologies are still used to a limited extent due to the lack of knowledge of the processes and the lack of the information on the optimal processing regimes for various alloys and technological processes of melting and casting.

Despite the fact that some of the above mentioned methods require the use of complex and expensive equipment, as well as the strict control of the temperature and time modes of melting, they contribute to the increase in the number of crystallization centers and grain structure refinement in comparison with the

V.B. Deev
Wuhan Textile University, Wuhan, China; National University of Science & Technology (MISIS), Moscow, Russia

E.S. Prusov
Vladimir State University named after Alexander and Nikolay Stoletovs, Vladimir, Russia

A.I. Kutsenko
Siberian State Industrial University, Novokuznetsk, Russia

methods of chemical grain refinement where the effect of their application strongly depends on the uniform distribution of the additive in the melt is limited in time in some cases, and the grain refining elements themselves can influence the change in the chemical composition of the alloy [26]. In addition, the methods of physical impact on the melt allow the use of up to 100% scrap and waste products in the furnace charge in some cases [27, 28]. The best results from the point of view of obtaining cast aluminum alloys and castings of a given quality, especially with an increased amount of scrap and waste in the charge, can certainly be achieved with the complex application of various physical methods of the grain refinement, for example, by complex melt processing using thermo-temporal treatment and vibration, or thermo-temporal treatment and electric current, etc. However, in industrial casting technologies, insufficient attention is paid to the complex methods of treating melts by physical action.
Before the beginning of the melt treatment by physical methods, it is desirable to analyze various variants of its processing and to choose the most suitable method for given castings production conditions. Within this framework, the actual task is the elaboration and experimental proof of a reliable computational and analytical technique that makes it possible to assess the effectiveness of various physical methods of melt processing.
The purpose of this paper is a comparative evaluation of various methods of aluminum melt processing by superimposing physical actions on the results of theoretical calculations and experimental data.

MATERIALS AND METHODS

A hypoeutectic aluminum alloy A356 (equivalent to the designation EN AB-42100 according to EN 1676-2010 specifications) has been used as a research subject. Chemical composition of alloy is given in Table. 1.

Tab. 1 – Chemical composition of the A356 alloy (EN AB-42100), wt.%

Al	Si	Mg	Fe	Cu	Mn	Zn	Ti	Others	
								each	total
bal.	6.5-7.5	0.30-0.45	≤0.15	≤0.03	≤0.10	≤0.07	≤0.18	≤0.03	≤0.10

The charge has consisted of 10 ... 15% of pig alloys and 85 ... 90% of recycled materials (scrap and waste of A356 alloy). Experimental meltings have been carried out in the alumina crucible in the electric resistance furnace. The alloy has been subjected to various physical actions during melting and molding for the comparative evaluation of their effectiveness. The conditions of experimental meltings and melt treatment parameters are given in Table 2.

Tab. 2 – Technological modes for melt treatment by physical actions

N°	Method and modes of melt treatment
1	Initial melt (untreated)
2	Thermo-temporal treatment : T = 1000 ^{0}C, τ = 8…12 min
3	Vibration in vertical direction: amplitude 1…1,2 mm; frequency 50 Hz
4	Thermo-temporal treatment (T = 1000 ^{0}C, τ = 8…12 min) + vibration (amplitude 1…1.2 mm, frequency 50 Hz)
5	Direct electric current with density $j = 0{,}92 \cdot 10^5$ A/m^2 at solidification
6	Thermo-temporal treatment (T = 1000 ^{0}C, τ = 8…12 min) + direct electric current with density $j = 0.92 \cdot 10^5$ A/m^2 at solidification
7	Argon: purging time 5…6 min at pressure 0.3 MPa
8	Thermo-temporal treatment (T = 1000 ^{0}C, τ = 8…12 min) + argon: purging time 5…6 min at pressure 0,3 MPa

Thermo-temporal treatment modes have been the same for all melt processing variations: superheating to 1000 °C, holding for 8 ... 10 min in the inert gas atmosphere (argon), cooling to the treatment temperature by the second physical action in the combined processes (750 °C) or to the pouring temperature (740 °C). In all cases, the melt have been degassed with manganese chloride (0.2%) before pouring. During crystallization processing of the molding with a direct electric current of j = 0.92 · 10^5 A/m^2 current density and I = 30 A current strength using a standard current source delivered to the sand form has been carried out. Argon blowing has been carried out by means of a lance injected into the melt; the blowing time has been 5 ... 6 min at a pressure of 0.3 MPa. To create vibration (1 ... 1.2 mm amplitude, 50 Hz frequency), a special vibrating table whose vibratory impulse transferred to a casting form through a metal platform in a vertical axial direction has been used.

To determine the theoretical amount of the solid phase falling out near the solidus temperature during the melt crystallization, and the total time of its crystallization, a special calculation technique has been developed. This technique is based on the determination of the alloys crystallization parameters related to fluidity. Fluidity of casting alloys is the most important property determining the production of castings of a desired quality, and depends on the amount of solid phase falling out near the solidus temperature. At a critical amount of the solid phase (from 25 to 30% for various alloys), the melt ceases to flow. Therefore, knowledge of the solid phase amount, as well as the total crystallization time of the alloy τ_n is essential in the castings production.

The fraction of the solid phase m_{OM}, falling out near the solidus temperature, has been calculated by the derived formula:

$$m_{OM} = \frac{\frac{\Lambda_M}{\Lambda_0}\left(\Delta T + m_0\left(\Delta T_{LS} + \frac{L_f}{c}\right)\right)_0 - \Delta T}{\Delta T_{LS} + \frac{L}{c}}, \quad (1)$$

where Λ_M, Λ_0 is the fluidity of the modified (treated) and unmodified (untreated) alloy, respectively; ΔT is the overheating interval above the liquidus temperature of the untreated alloy; m_0 is the solid fraction at crystallization of the untreated alloy ($m_0 = 0.30$ has been assumed for the calculations); ΔT_{LS} is the interval of the untreated alloy crystallization; L_f is the latent heat of the melt crystallization; c is the melt heat capacity.

The formula (1) for calculating the mass fraction of the solid phase m_{OM} for a modified alloy at a known value of m_0 for the initial alloy was derived by mathematical transformations of the conventional heat balance equations for the heat transfer processes between melt and mold [29], classical dependences of the theory of fluidity of metallic melts [30], and also taking into account the lever rule for the Al-Si phase diagram under the assumption that the melt crystallizes under equilibrium conditions [31].

The calculated value of the casting total crystallization time has been determined by the Chvorinov's rule [32]:

$$\tau = \frac{\pi}{4\lambda_m \rho_m c_m}\left(\frac{\rho_S L_f}{T_f - T_0}\right)^2 \left(\frac{V}{A}\right)^2, \quad (2)$$

where λ_m is the thermal conductivity of the mold; ρ_m is the density of the mold material; c_m is the mold material heat capacity; ρ_s is the density of the solid metal; L_f is the latent heat of crystallization; T_f is the melting point of the metal; T_0 is the initial temperature of the mold; A is the form and metal separation surface area; V is the volume of the casting.

The experimental determination of the solid fraction m_{OM} and the alloy total crystallization time τ_n has been carried out using direct thermal and differential thermal analysis methods at the solidification of cylindrical samples of 300 mm of length and 26 mm of diameter in the sand form. The experimental technique is suitable when performing computer thermal analysis of melts crystallization using Computer Aided Cooling Curve Analysis (CA-CCA) methods [33].

To determine of the solid phase volume fraction in the solidifying sample by the CA-CCA method, the following mathematical model has been used. At each timepoint the solid phase volume fraction in the crystallization interval of the alloy can be calculated according to [34] by the following equation:

$$\varphi(t) = \frac{V_S(t)}{V_0} = k(T)\int_{t_L}^{t}(T(t) - T_0)dt + \frac{(T(t) - T_L)}{\Delta T(t_S) - \exp(-\alpha t_S)} \quad (3)$$

where V_0 and V_s are the volume of the melt sample and the volume of the solid phase, respectively; t_L is the timepoint when the melt reaches the liquidus temperature; T is the temperature of the melt sample; T_L and T_S are the liquidus and solidus temperatures of the alloy, respectively; $T(t)$ is the sample temperature as a function of time; T_0 is the ambient temperature; α is the coefficient of heat transfer; t_s is the end of the alloy solidification; $k(T)$ is a coefficient that can be determined empirically for the sample state, when $\varphi(t_s)=1$ is a fully solidified sample or more precisely calculated according to equation

$$k(T) = \frac{\alpha F}{L_f \rho V_0} \qquad (4)$$

where F is the surface area of the sample; ρ is the density of the alloy; L_f is the latent solidification heat; α is the heat transfer coefficient which is depends on the sample temperature and can be calculated by following equation:

$$\alpha = a_0 + \int_{i=1}^{3} a_i T^i. \qquad (5)$$

To determine the temperatures of the beginning and the end of solidification of alloys, the curves of the differential thermal analysis of the crystallizing sample have been used (Fig. 1). The solidus temperature has been calculated on the basis of the analysis of the first derivative of obtained thermogram $T'(t)$, liquidus – based on the analysis of the second derivative of thermogram $T''(t)$. The wavelet transform of the signal based on the normalized second derivative of Gaussian has been used to determine the liquidus temperature at high noise interference of temperature measurements.

The alloys fluidity has been determined from a horizontal round rod sample of 5 mm in diameter and 450 mm in length, poured into the steel mold in a gravity casting conditions (commercially available test method for measuring fluidity; one of its examples described by F. Binczyk et al. [35]). The mold temperature before pouring was kept constant at 200 °C (measured by a calibrated K-type thermo-couple installed at the mold center). Pouring temperature for all variants has been 725 ... 730 °C. The mold was coated with a zinc oxide to the thickness about 0.3 mm. To ensure reproducible hydraulic conditions of the mold filling in all experiments, the head height was the same and equal to 100 mm. To realize this, a stopper rod was installed in the pouring cup, which was raised after complete filling the cup with a melt. The number of test samples for calculating the mean value of fluidity for each variant of melt processing technology was 10. The samples mi-crostructure has been examined in as-cast state by a Carl Zeiss Axiovert 200M inverted microscope. Mechanical properties of the alloys have been determined on standard samples with a working diameter of 10 mm on the universal testing machine Electronic Universal Testing Machine WDW-100E. When studying the properties of the experimental alloys in the course of the direct measurements, the arithmetic average and confidence intervals of the obtained values of the measured quantity have been calculated for each series of experiments.

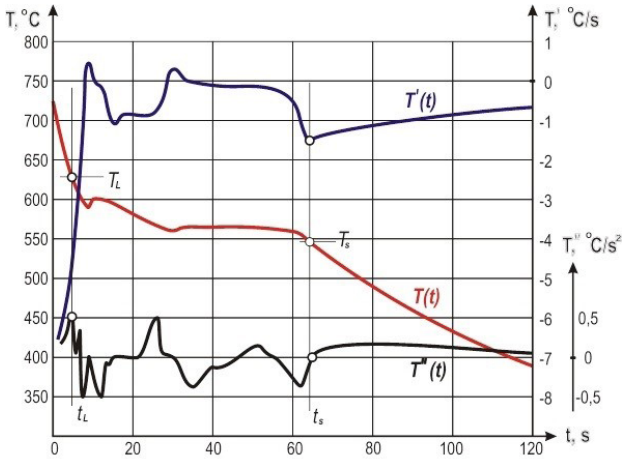


Fig. 1 – Typical thermogram of A356 alloy

RESULTS AND DISCUSSION

The calculated and experimental values of the total solidification time and the solid fraction as exemplified in A356 alloy treated by different physical methods are shown in Fig. 2 and 3.

The analysis of the obtained data indicates that physical actions affect the melt crystallization parameters, increasing the total solidification time and the solid fraction falling out near the solidus temperature. It has been assumed that external physical effects on melts contribute to a decrease of the separating diffusion rate near the liquidus temperature and a shift of the crystallization process to the lower temperatures area so the fraction of the solid phase formed near the solidus temperature increases with respect to the base alloy for the treated alloys. After the treatment by physical action the melt is able to retain fluidity at a relatively high fraction of the formed solid phase. In melt treatment the most effective are variants 2 and 8, in which m_{OM} corresponds to 0.41 and 0.42 according to the calculations, 0.38 and 0.39 according to the experimental data.

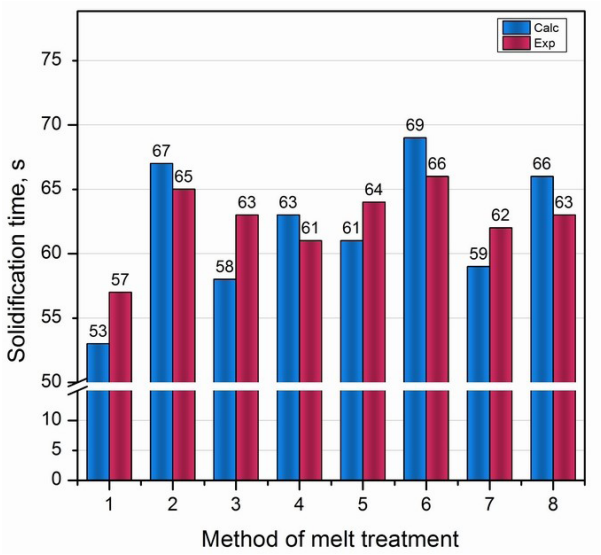


Fig. 2 – Calculated and experimental values of the total solidification time τ_n of the alloy sample, s (numbers of melt treatment variations correspond to those indicated in Table 2).

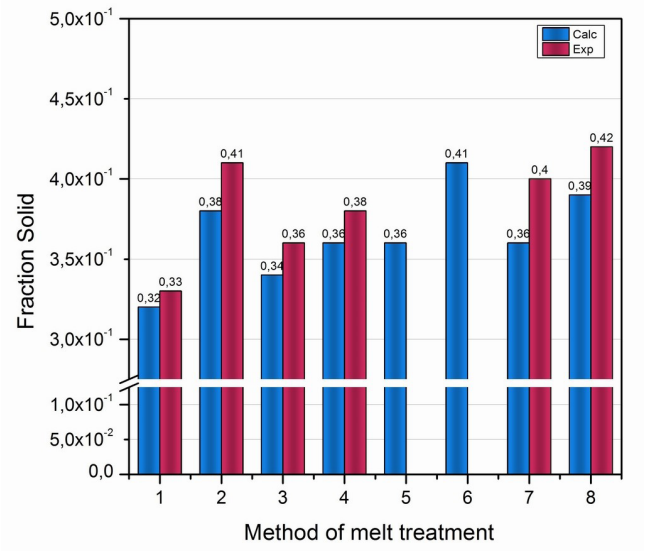
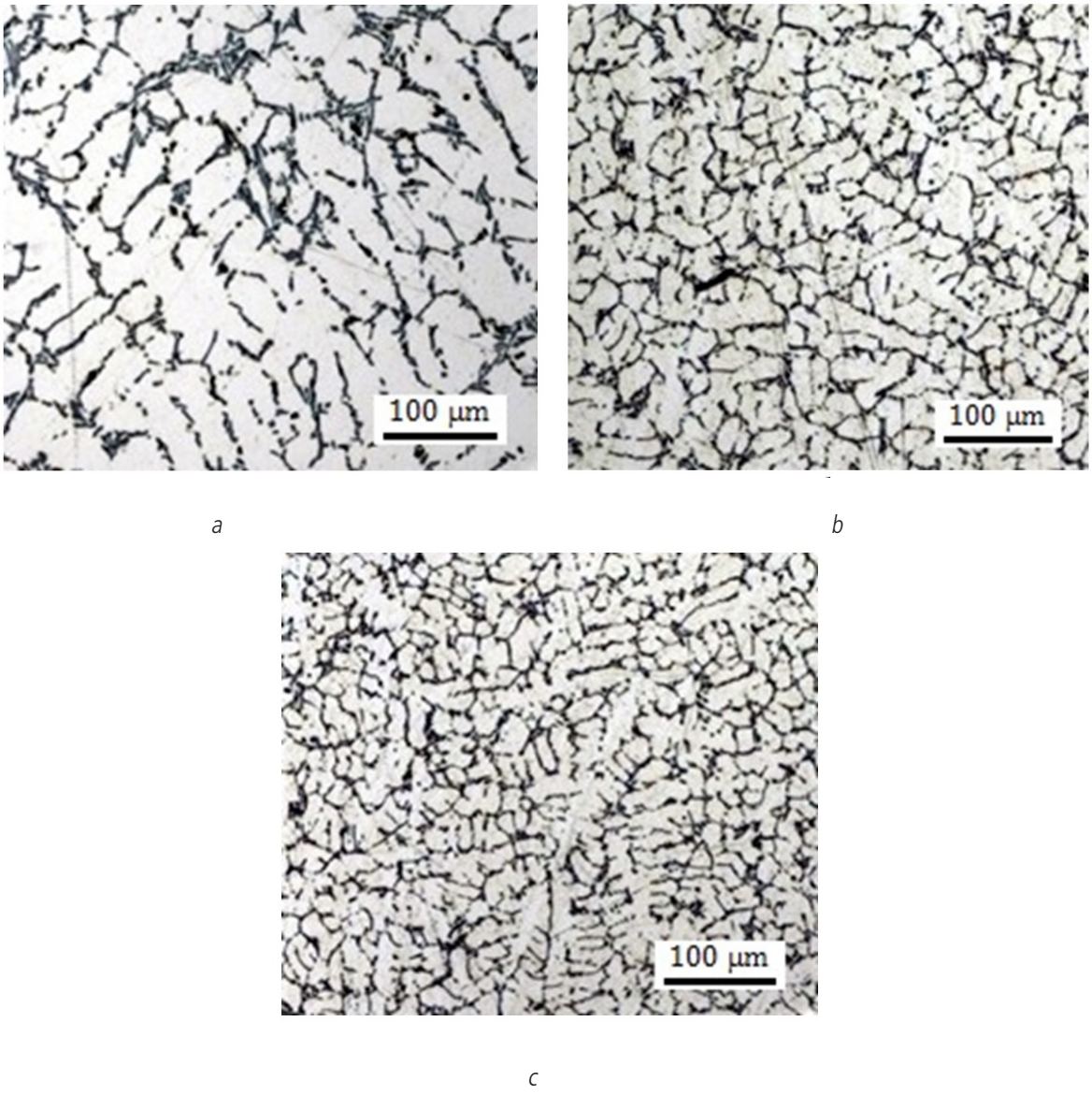


Fig. 3 – Calculated and experimental values of the solid phase fraction m_{OM} (numbers of melt treatment variations correspond to those indicated in Table 2).

Fig. 5 shows the optical micrographs of the A356 alloy structure in the initial state (variant 1) and after the melt treatment (variants 2 and 8). It can be seen that during treatment there is a substantial reduction of both the size of the dendritic cell and of the eutectic structure. These observations testify to the complex effect of the applied treatment methods and the effectiveness of their application for refining the grain structure of the alloys of the Al-Si system.



a *b* *c*

Fig. 4 – Microstructure of the experimental alloys: *a* – initial alloy (untreated); *b* – melt processing technology according to variant 2 (Table 2); *c* – melt processing technology according to variant 8 (Table 2).

Results of the investigations of mechanical properties (ultimate tensile strength UTS and elongation δ) and the alloy fluidity (Λ) at using of different physical methods of melt treatment are presented in Table. 3.

Tab. 3 - Mechanical and technological properties of A356 alloy (as-cast condition) depending on the melt processing method

Variant	Method of melt treatment	UTS, MPa	δ, %	Λ, mm
1	Initial alloy (untreated)	190 ± 3	2.8 ± 0.3	96 ± 2.80
2	Thermo-temporal treatment	200 ± 5	3.5 ± 0.1	109 ± 2.72
3	Vibration	211 ± 7	4.2 ± 0.1	109 ± 3.26
4	Thermo-temporal treatment + vibration	219 ± 5	4.7 ± 0.3	115 ± 3.68
5	Electric current	222 ± 3	5.2 ± 0.1	-
6	Thermo-temporal treatment + electric current	229 ± 4	5.9 ± 0.2	-
7	Inert gas purging	223 ± 5	5.8 ± 0.1	120 ± 2.88
8	Thermo-temporal treatment + inert gas purging	228 ± 2	6.1 ± 0.3	126 ± 3.17

The obtained experimental data confirmed the positive effect of complex treatment by physical methods. Fluidity of the experimental alloys, determined by reference to the test sample, increased by an average by 18 ... 25%, herewith the best results have been achieved for variant No. 8 (+ 31.3%). The most significant increase in the strength characteristics of the A356 alloy has been recorded after the combined thermo-temporal treatment and application of electric current during crystallization (+ 20.5%) as well as thermo-temporal treatment and inert gas purging (+ 20%), with that two-fold ductility increase in each of the indicated treatment variants has been mentioned.
Thus, with the employment of the complex technologies for melts treating, the use of the preliminary thermo-temporal treatment enhances the grain refining effect of the second physical action greatly. This turned out to be characteristic for all melt processing options. The best results have shown the options of the combined use of thermo-temporal treatment with an inert gas (No. 8), or with electric current (No. 6). The stated increase of the alloy mechanical properties are conditioned by the refining of its structural constituents.
Treatment by electric current during crystallization is promising in the production of castings from secondary aluminum alloys containing iron impurity. The positive effect of such treatment can be expressed in a change in the dispersability and morphology of iron-containing phases. However, the mechanism of the electric current impact on the process of alloys crystallization has not yet been sufficiently investigated both in the experimental and in the theoretical aspects. The possibility of using thermo-temporal treatment in the production of castings from low-grade charge materials with elevated iron content should also be considered [36].
A promising direction for further research is the investigation of the physical actions influence the formation of cast aluminum matrix composites structure and properties [37-39]. It has been assumed that the application of external physical action during melting and casting will allow to control the composites structure purposefully, providing a desired degree of interphase interaction between the matrix material and the reinforcing phase, as well as the uniform distribution of reinforcing components in the melt volume.

CONCLUSIONS

It has been shown that processes of casting aluminum alloys crystallization can be determined to a great extent by the technology of processing by physical influences during melting and casting. These technologies, provided they are used rationally, can significantly improve the quality of the obtained cast products.
The technique for estimating the effectiveness of various physical actions on melts based on the determination of the solid phase fraction falling out near the solidus temperature during the alloys crystallization has been proposed and tested. The predictive calculations by this technique are in good agreement with the experimental data of thermal and differential thermal analysis. The technique is recommended for selecting the most rational and effective physical methods for melts processing on the predicted values of the crystallization parameters of aluminum alloys.

Despite the fact that the use of physical methods for melts processing in industrial conditions leads to some increase in the production cost of castings due to additional power energy costs, this increase is compensated due to the absence the need to use expensive refining additives to provide the desired structure and properties of castings with increased operational requirements.

The obtained data on the changes in the structure and properties of aluminum alloys indicate that the physical methods of melt treatment (thermo-temporal treatment, electric current during crystallization, etc.) can be successfully applied in foundries in the production of castings for critical duty applications, for which strict limitations on the content of impurity elements have been established. Physical methods make it possible to produce high quality castings with a modified structure without using refining additives influencing the chemical composition of the alloy.

ACKNOWLEDGMENTS

The work has been carried out within the framework of the state work "Organization of Scientific Research" of the Ministry of Education and Science of Russia of the state task in the field of research for 2017-2019 (Task No. 11.5684.2017 / 6.7).

REFERENCES

[1] Sigworth G.K., Kuhn T.A. Grain refinement of aluminum casting alloys // International Journal of Metalcasting (2007), 1: 31-40.
[2] Li P., Liu S., Zhang L., Liu X. Grain refinement of A356 alloy by Al–Ti–B–C master alloy and its effect on mechanical properties // Materials & Design (2013), 7: 522-528.
[3] Meena P.C., Sharma A., Singh S. Effect of grain refinement on microstructure and wear behavior of cast Al-7Si alloys // La Metallurgia Italiana (2015), 1: 25-34.
[4] Wannasin J., Canyook R., Wisutmethangoon S., Flemings M.C. Grain refinement behavior of an aluminum alloy by inoculation and dynamic nucleation // Acta Materialia (2013), 61: 3897-3903.
[5] Easton M.A., Qian M., Prasad A., St. John D.H. Recent advances in grain refinement of light metals and alloys // Current Opinion in Solid State and Materials Science (2016), 20: 13-24.
[6] Guan R.G., Tie D. A Review on grain refinement of aluminum alloys: progresses, challenges and prospects // Acta Metallurgica Sinica (2017), 30: 409-432.
[7] Vorozhtsov S., Kudryashova O., Promakhov V., Dammer V., Vorozhtsov A. Theoretical and experimental investigations of the process of vibration treatment of liquid metals containing nanoparticles // JOM (2016), 68: 3094–3100.
[8] Eskin D.G. Ultrasonic processing of molten and solidifying aluminium alloys: overview and outlook // Materials Science and Technology (2017), 33: 636-645.
[9] Zhang Y., Svynarenko K., Li T. Effect of ultrasonic treatment on formation of iron-containing intermetallic compounds in Al-Si alloys // China Foundry (2016), 13: 316–321.
[10] S. Komarov, Y. Ishiwata, I. Mikhailov. Industrial application of ultrasonic vibrations to improve the structure of Al-Si hypereutectic alloys: Potential and Limitations // Metallurgical and Materials Transactions A (2015), 46: 2876-2883.
[11] Rabiger D., Zhang Y., Galindo V., Franke S., Willers B., Eckert S. The relevance of melt convection to grain refinement in Al-Si alloys solidified under the impact of electric currents // Acta Materialia (2014), 79: 327-338.
[12] Prodhan A. Semi-solid processing by electric current during sand casting of aluminium alloys // IOP Conf. Series: Materials Science and Engineering (2016), 115: 012005.
[13] Y. Zhang, D. Rabiger, B. Willers, S. Eckert. The effect of pulsed electrical currents on the formation of macrosegregation in solidifying Al-Si hypoeutectic phases // International Journal of Cast Metals Research (2017), 30: 13-19.
[14] Zhang, Y., Cheng, X., Zhong, H., (...), Song, C., Zhai, Q. Comparative study on the grain refinement of Al-Si alloy solidified under the impact of pulsed electric current and travelling magnetic field // Metals (2016), 6, 170.
[15] Bustos O., Ordoñez S., Colás R. Rheological and microstructural study of A356 alloy solidified under magnetic stirring // International Journal of Metalcasting (2013), 7: 29-37.
[16] Wang X.., Luo X., Cong F., Cui J. Research progress of microstructure control for aluminium solidification process // Chinese Science Bulletin (2013), 58: 468–473.
[17] Chen H., Jie J., Fu Y., Ma H., Li T. Grain refinement of pure aluminum by direct current pulsed magnetic field and inoculation // Transactions of Nonferrous Metals Society of China (2014), 24: 1295–1300.
[18] Haghayeghi R., de Paula L.C., Zoqui E.J. Comparison of Si refinement efficiency of electromagnetic stirring and ultrasonic treatment for a hypereutectic Al-Si alloy // Journal of Materials Engineering and Performance (2017), 26: 1900–1907.
[19] Timoshkin I.Y., Nikitin K.V., Nikitin V.I., Deev V.B. // Influence of treatment of melts by electromagnetic acoustic fields on the structure and properties of alloys of the Al–Si system // Russian Journal of Non-Ferrous Metals (2016), 57: 419-423.

[20] Ivanov Y.F., Alsaraeva K.V., Gromov V.E., Popova N.A., Konovalov S.V. Fatigue life of silumin treated with a high-intensity pulsed electron beam // Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques (2015), 9: 1056–1059.
[21] Ivanov Y.F., Alsaraeva K.V., Gromov V.E., Konovalov S.V., Semina O.A. Evolution of Al–19.4Si alloy surface structure after electron beam treatment and high cycle fatigue // Materials Science and Technology (2015), 31: 1523–1529.
[22] Timelli, G., Fiorese, E. Metodi di neutralizzazione del Fe in leghe Al-Si da fonderia // La Metallurgia Italiana (2011), 103: 9-23.
[23] Li Q.L., Xia T.D., Lan Y.F., Li P.F. Effects of melt superheat treatment on microstructure and wear behaviours of hypereutectic Al-20Si alloy // Materials Science and Technology (2014), 30: 835-841.
[24] Peng J., Jinyang Z., Haoran G., Zhongxi Y., Xinying T., Degang Z., Yan W., Min Z., Ningqiang S. Effect of melt superheating treatment on solidification structures of Al75Bi9Sn16 immiscible alloy // Journal of Molecular Liquids (2017), 232: 457-461.
[25] Deev V.B., Selyanin I.F., Ponomareva K.V., Yudin A.S., Tsetsorina S.A. Fast cooling of aluminum alloys in casting with a gasifying core // Steel in Translation (2014), 44: 253-254.
[26] Selyanin I. F., Deev V. B., Belov N. A., Prikhodko O. G. Physical modifying effects and their influence on the crystallization of casting alloys // Russian Journal of Non-Ferrous Metals (2015), 56: 434-436.
[27] Deev V.B., Selyanin I.F., Kutsenko A.I., Belov N.A., Ponomareva K.V. Promising Resource Saving Technology for Processing Melts During Production of Cast Aluminum Alloys // Metallurgist (2015), 58: 1123-1127.
[28] Selyanin I.F., Deev V.B., Kukharenko A.V. Resource-saving and environment-saving production technologies of secondary aluminum alloys // Russian Journal of Non-Ferrous Metals (2015), 56: 272-276.
[29] Fredriksson H., Akerlind U. Solidification and Crystallization Processing in Metals and Alloys. John Wiley & Sons, Ltd. (2012).
[30] Campbell J. Casting, 2nd ed. Oxford: Elsevier, Butterworth-Heinemann (2003).
[31] Stefanescu D.M. Science and Engineering of Casting Solidification, 3rd ed. Springer International Publishing Switzerland (2015).
[32] Dantzig J.A., Rappaz M. Solidification. Taylor & Francis, Lausanne (2009).
[33] Sudheer R., Prabhu K.N. A Computer Aided Cooling Curve Analysis method to study phase change materials for thermal energy storage applications // Materials & Design (2016), 95: 198-203.
[34] Rafalski I., Arabey A., Lushchik P., Chaus A.S. Computer modeling of cast alloys solidification by Computer-Aided Cooling Curve Analysis (CA-CCA) // International Doctoral Seminar, Proceedings. Trnava: Alumni Press, 2009: 291-301.
[35] Binczyk F., Ciesla M., P. Gradon, R. Findzinski. Evaluation of casting shrinkage and liquid metal fluidity of IN-713C Alloy // Archives of Foundry Engineering (2014), 14: 9-12.
[36] Yang W., Yang X., Ji S. Melt superheating on the microstructure and mechanical properties of diecast Al-Mg-Si-Mn alloy // Metals and Materials International (2015), 21: 382–390.
[37] Timelli, G., Ferro, P., Bonollo, F. Compositi a matrice di alluminio solidificati in presenza di vibrazioni meccaniche: Caratteristiche microstrutturali // La Metallurgia Italiana (2010) 102.
[38] Prusov E.S., Panfilov A.A. Properties of cast aluminum-based composite alloys reinforced by endogenous and exogenous phases // Metally (2011), 7: 670-674.
[39] Nordin N., Abubakar T., Hamzah E., Farahany S., Ourdjini A. Effect of Superheating Melt Treatment on Mg2Si Particulate Reinforced in Al-Mg2Si-Cu In situ Composite // Procedia Engineering (2017), 184: 595–603.