The effect of ultrasonic degassing on the quality and properties of components produced by low and high pressure die casting

Introducing ultrasound in molten aluminium is known to be an efficient means of melt degassing without the need to use expensive gases and rotating parts. In this paper the performance of ultrasonic degassing with regard to the quality and tensile properties of cast parts is compared with conventional Ar rotary degassing for two common casting techniques, low-pressure and high-pressure die casting. A significant reduction in dross formation is observed after the ultrasonic degassing treatment than after the conventional Ar rotary degassing. The mechanical properties and porosity level of components produced by low pressure die casting and high pressure die casting after both degassing techniques are determined. The results show that the components produced after ultrasonic degassing have similar tensile properties and porosity level as the components degassed with the conventional Ar rotary degassing.

Thomas Pabel and Tose Petkov, Leoben, Austria, Manel da Silva, Cerdanyola del Vallès, Spain, Renáta Ruzsinszki, Sátoraljaújhely, Hungary, Xavier Planta and Jaume Tort, Cerdanyola del Vallès, Spain, Dmitry Eskin, Uxbridge, United Kingdom / Tomsk, Russian Federation

Manuscript received 2 February 2015; accepted 12 March 2015

1 Introduction

Degassing of aluminium melt is a standard procedure in cast houses and most of foundries. The practical importance of degassing for liquid aluminium comes from highly variable solubility of hydrogen that is quite high in the liquid aluminium and very small in the solid aluminium. As a result, during solidification the excess hydrogen precipitates and beings trapped between solid aluminium grains forms gas porosity or contributes to shrinkage porosity. This porosity is a major casting defect causing poor ductility, decreased fatigue resistance and strength of a casting [1].

Hydrogen finds its way into liquid aluminium through atmospheric moisture (water vapour reacts with aluminium to produce alumina and hydrogen) and hydrocarbon-containing gases in furnace atmosphere. The quasi-equilibrium concentration of hydrogen in the liquid aluminium phase is therefore a function of atmospheric pressure, temperature and humidity as described by G. S. Makarov [2] and P. Le Brun [3] and recently reported by D. Eskin et al. [4] for ultrasonic degassing. This quasi-equilibrium limit may rise to high values in a humid atmosphere. The degassing may decrease the amount of dissolved hydrogen below the quasi-equilibrium concentration but then the degassed melt will tend to re-gas, absorbing hydrogen from the ambient humidity and restoring the quasi-equilibrium values [1, 4].

Ultrasonic degassing of liquid metals has a long history that is reviewed elsewhere [5]. One of the first attempts were made in the 1940s by W. Esmarch et al. [6] who reported the degassing of Al-Mg alloys by sonic oscillations induced by contactless electromagnetic stirring and vibrations in the crucible. G. Bradfield [7] reported the works of Turner on ultrasonic degassing of molten aluminum and its alloys by direct introduction of ultrasonic oscillations into the melt. The comparison of vacuum ultrasonic degassing with vacuum degassing, degassing with chlorine lancing, and sonic and ultrasonic degassing was performed by H. Eisenreich [8]. The potential of ultrasonic processing was shown but also practical difficulties related to equipment were noted. S. V. Sergeev [9] specified that despite high potential of ultrasonic degassing there is a challenge in transferring sufficient ultrasonic power to a large mass of liquid metal.

O. A. Kapustina [10] gave a thorough analysis of ultrasonic degassing mechanisms in water and concluded that the most important role is played by the oscillations of the bubbles in the acoustic field, while ultrasonic cavitation takes the supportive role in intensification of the bubble formation and acceleration of bubble / liquid interfacial diffusion. G. I. Eskin [11, 12] argued that the cavitation is essential for ultrasonic degassing of metallic melts where the free gas bubbles are not typically present, unlike those in water. Therefore, the formation and multiplication of bubbles (essential for degassing) can be only achieved in liquid metals by cavitation. Indeed, already early investigations conducted by M. B. Altman et al. [13] demonstrated that the removal of hydrogen from aluminium alloys depended greatly on the acoustic power transferred to the melt and on the development of cavitation.

Starting from the 1960s successful laboratory and pilot-scale trials of ultrasonic degassing for foundry and later wrought alloys have been performed and summarized in a series of publications by G. I. Eskin [11, 14]. In these works the practical issues such as equipment selection (water-cooled magnetostrictive transducers) and sonotrode materials selection (Nb and Nb-based alloys) were solved and justified. However, the scaling-up of the ultrasonic degassing to treating larger melt volumes (hundreds of kg) was done by multiplying the number of ultrasonic transducers and sonotrodes. This way demonstrated its feasibility in degassing commercial quantities of aluminium melt but was not widely implemented due to the bulkiness and low reliability of equipment.

In addition, Ar-assisted rotary or impeller degassing was developed by the beginning of the 1980s and became the mainstream degassing technology that is currently widely used [15]. Despite being quite efficient in removal of hydrogen and partially oxide inclusions, Ar-assisted degassing has some drawbacks including large dross formation due to the melt turbulence, high consumption of an expensive and energy-consuming noble gas, and the use of fragile graphite impellers that may break contaminating the melt.

The intrinsic features of ultrasonic degasing such as absence of rotating parts, no requirement for gas usage and clean environment stipulated comeback interest to this technology that may answer the recent environmental challenges. In addition, modern reliable ultrasonic technology makes its application technologically easier.

This paper reports the results of pilot-scale trials of ultrasonic degassing (UD) as applicable to major foundry technologies, i. e. low-pressure (LPDC) and high-pressure die casting (HPDC). The objective of the equipment and technology development was to achieve degassing of commercially relevant quantities of melt with the use of a single ultrasonic source. In our previous work we showed that the degassing efficiency of both tested degassing techniques was similar. Up to 150 kg of the melt can be degassed using ultrasonic processing to the same extent as by conventional Ar rotary degassing and within the same time frame [16]. In this paper we focus on the evaluation of cast components.

2 Experimental procedure

2.1 Ultrasonic degassing equipment

Two different machines were developed to degas the molten aluminium alloys in different casting processes. One of the prototypes was specifically designed for HPDC. This degassing unit comprises a heated degasing chamber where the degassing takes place and from where the degassed melt is automatically dosed into the cold chamber of the shot sleeve (**Figure 1**). The melt in the degassing chamber is under reduced pressure during degassing and elevated pressure during dosing.

The second machine was projected to treat larger volumes of molten aluminium, in order to degas a standard melt transport ladle (from 200 to 800 kg). The device allowed for the movement of an ultrasonic transducer with a sonotrode both vertically and circumferentially, as shown in **Figure 2**.

The ultrasonic equipment used in the prototypes included: a USGC-5-22 MS ultrasonic generator, a MST-5-18 water-cooled magnetostrictive transducer, a titanium booster,

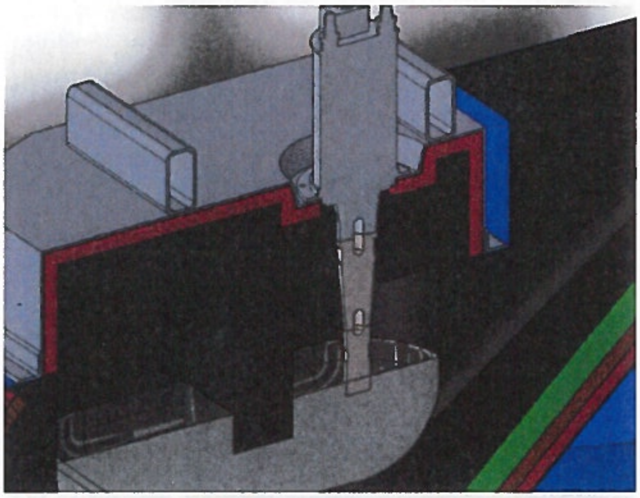

Figure 1: Scheme of an ultrasonic degassing machine specifically intended for HPDC

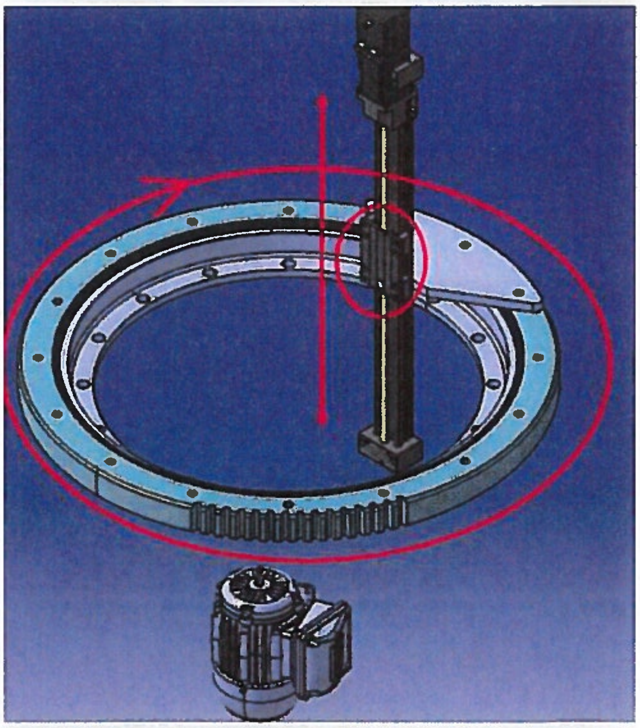

Figure 2: Functioning scheme of an ultrasonic degassing setup designed to treat large volumes

supplied by Reltec (Russia), and a custom-made niobium tip. **Figure 3** shows the assembled ultrasonic degassing equipment used in the LPDC trials. The vibration amplitude at the tip of the sonotrode was 25 µm and the frequency was 17.5 kHz.

2.2 Melt treatment procedure

A commercially available AlSi9Cu3Fe (A380) alloy was used for HPDC components and a commercially available AlSi7Mg0.3 (A356) alloy was used for LPDC components.

The A380 alloy was melted in an electrical furnace and then 100 kg of the melt was transferred to the degassing machine shown in Figure 1. The melt temperature was maintained at 700 ± 5 °C. The ultrasonic degassing was performed for 15 min. A portion of the melt was then dosed out to the shot sleeve of a Buhler 400 T machine and injected into a die, producing real industrial components, 1.45 kg net weight.

The ultrasonic degassing parts were compared with standard components produced with the same alloy casting parameters (degassing time 15 min, melt temperature 700 °C). The only difference is that instead of ultrasonic degassing the melt was degassed in the holding furnace by argon lancing using a graphite lance.

The melt intended for LPDC was modified with 200 ppm of Sr. The metal was molten and heated to a temperature of 725 ±5 °C in an electrical furnace with an inner clay-graphite crucible with a diameter of 500 mm and a depth of 500 mm (Nabertherm, Germany). The total amount of melt was 150 kg.

The degassing process was done using two different methods, a conventional Foseco degassing unit with Ar purging (FDU) and the ultrasonic prototype (see Figure 3). The ultrasonic and rotary degassing treatments were both applied for 15 min to a melt at a temperature of 725 ±5°C. During ultrasonic treatment the sonotrode was moving circumferentially at 1 rpm with up and down movement with a range of 30 mm resulting in the submerge depth 40 to 70 mm. For the rotary degassing the Ar flow was 6 l/min.

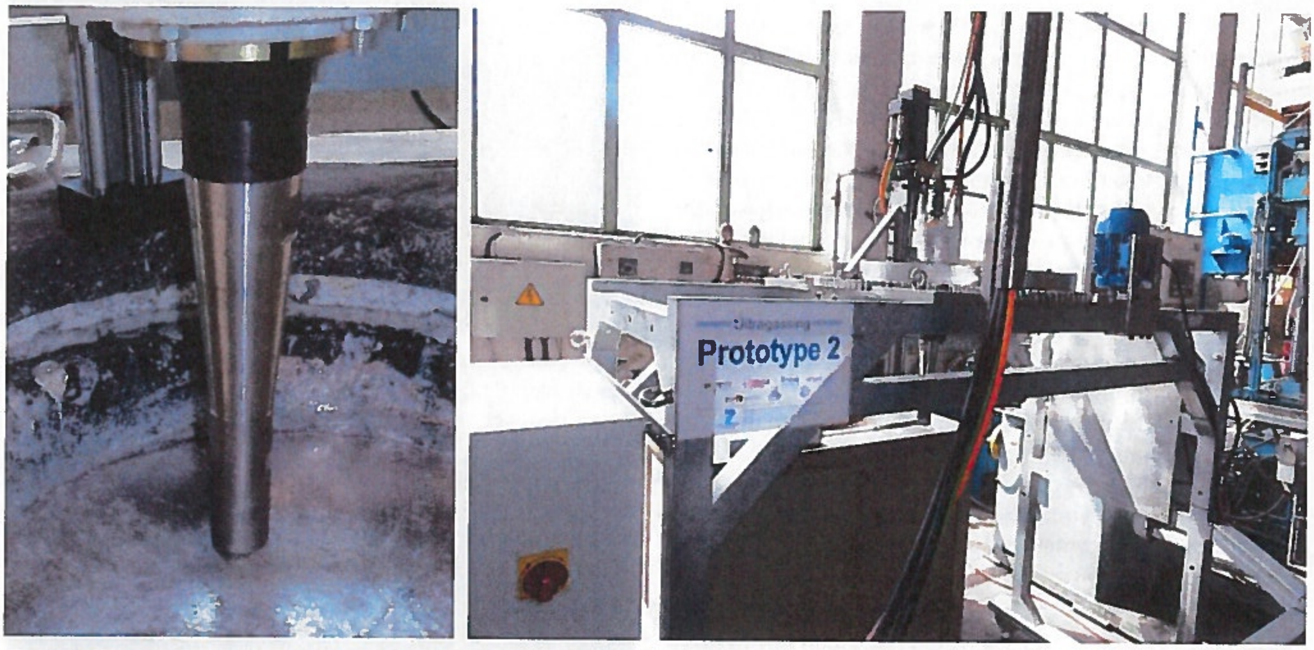

Figure 3: Waveguiding system (left) and ultrasonic degassing prototype (right)

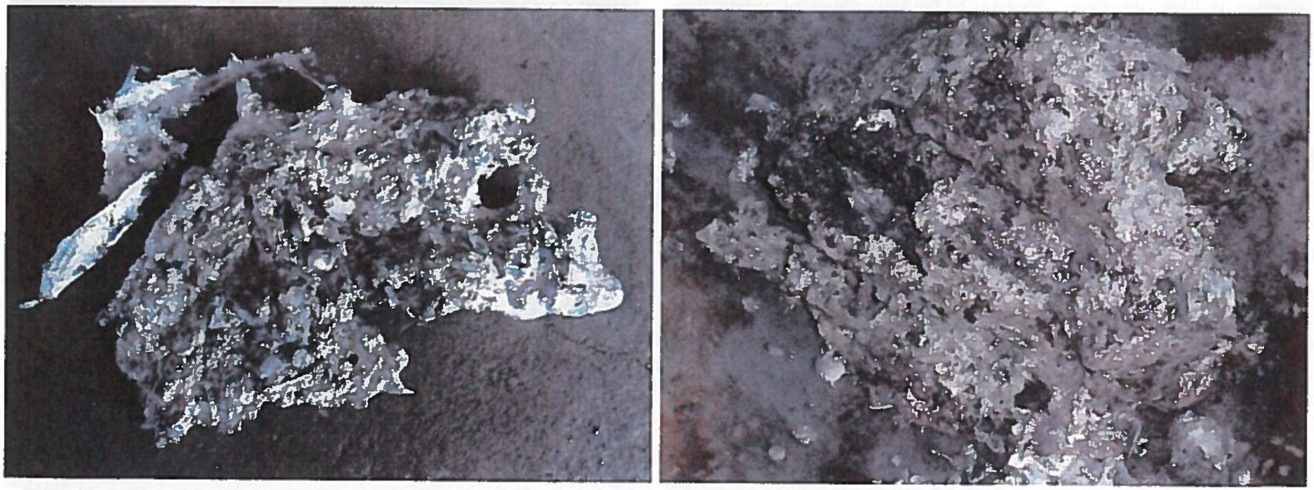

Figure 4: Dross after ultrasonic degassing treatment (left) and after Ar rotary degassing treatment (right)

The casting was performed in a Kurtz AK92 LPDC machine. For the casting production melt was transferred from the melting furnace where degassing was performed to the LPDC furnace.

2.3 Component casting and evaluation

The porosity present in the components was analysed by computed tomography. A V|tome|x c equipment with an DXR-250RT area detector, an acceleration voltage of 165 kV and a current of 250 µA was used for the evaluation. The recorded tomograms were processed in software "Volume Graphics Studio Max", version 2.2.

In addition, from each part 4 tensile bars were machined according to DIN 50125 – B 5 x 25. In the subsequent tensile tests according to EN 10002-1, the 0.2 % yield strength $R_{p0.2}$, the tensile strength R_m and the elongation at fracture A were determined in a universal testing machine (Zwick Roell 250 kN).

3 Experimental results and discussion

3.1 Dross formation

The formation of dross on the molten aluminium was monitored by skimming the melt surface, weighing and visual examination. **Figure 4** exhibits the dross skimmed after ultrasonic degassing and after Ar rotary degassing trials. The quantitative results are compiled in **Table 1**.

Table 1: Dross formation

	Weight		Comment
	[g]	[%]	
After FDU	1800	1.20	Extremely high metallic content
After US	340	0.23	Low metallic content

The results obtained demonstrate an added value of ultrasonic degassing over conventional rotary degassing. Dross formation is related to the disturbance of the melt surface with entrapment of existing and formation of new oxide films. This oxide layer with inclusions of aluminum (50-80 %) gradually builds up at the surface and should be removed before casting, representing direct metal losses [1]. The recovery of aluminium from the dross is an energy-consuming operation that requires special processing outside the foundry. Rotary degassing using impeller and gas purged through the melt from the bottom creates highly turbulent conditions in the melt with forced upward bubble movement and vortex formation at the melt surface, enhancing dross formation as reported by [17].

Ultrasonic degassing treatment, on the contrary, creates very small cavities that are turned into hydrogen bubbles, with the flow direction downwards. These bubbles then grow in the acoustic field, extracting hydrogen dissolved in the liquid phase, and naturally float to the surface without turbulence and surface disturbance. As a result, dross formation is limited.

It is known that gas-assisted degassing cleans of the melt also from oxide inclusions that adhere to the bubble surface and float along to the surface [17]. Ultrasonic degassing should have similar effect as reported elsewhere [14], with oxide inclusions being associated with cavitation bubbles. Cleaning of the melt from oxide inclusions cannot, therefore, explain the massive difference in dross formation in the two tested degassing techniques.

3.2 Porosity

The porosity in the components was determined by tomographic analysis. **Figure 5** gives the images taken from the components produced by HPDC. The total volume of voids detected was 1260 mm^3 in the case of the component submitted to ultrasonic degassing and 1004 mm^3 on the component degassed with Ar bubbling. Therefore, the amount of porosity detected in both components is in the same level.

The LPDC components revealed a similar behaviour. **Table 2** presents the number of pores detected for each volume interval in the LPDC components for both degassing processes.

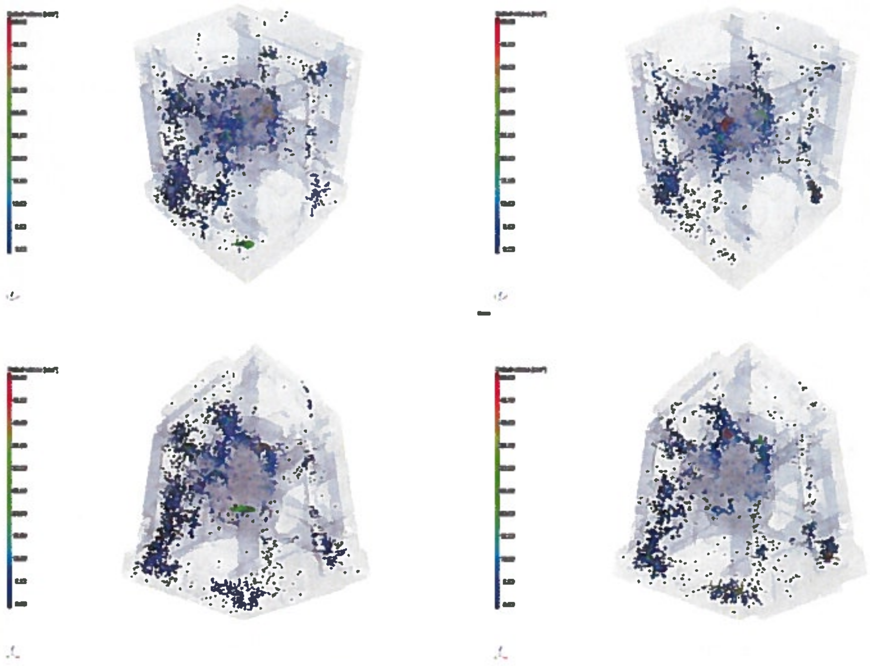

Figure 5: Area porosity in 3D-view of componenst subjected to ultrasonic degassing treatment (left) and Ar rotary degassing (right)

Although the total number of pores in the cast components is similar for both degassing techniques (which is a reasonable result providing the similar hydrogen concentration in the melt after degassing [16]), the porosity size distribution tends to shift to smaller pores in the case of ultrasonic degassing for both casting processes (HPDC and LPDC).

3.3 Mechanical properties

Table 3 presents the average tensile properties obtained for the components produced by HPDC after both degassing technologies. These results do not show any significant differences in the mechanical properties between two degassing processing routes.

In the same direction point the results obtained with the specimens tested for each degassing process for the components produced by LPDC. There is an indication that in the case of LPDC the US-degassed samples have a higher elongation than the impeller-degassed samples.

Table 2: Number of pores detected by tomography on the LPDC components for both means of degassing

Equivalent spherical diameter, µm	Volume, mm^3	Number of pores (impeller)	Number of pores (ultrasound)
0-100	0-0.00052	12	30
101-250	0.00054-0.00818	2802	2891
251-450	0.00828-0.04771	2507	2136
451-700	0.04803-0.17959	14	0
701-1000	0.18037-0.5236	0	0
>1001	>0.52517	0	0

Table 3: Tensile properties of cast components produced after degassing using either Ar rotary or ultrasonic technology

Degassing technology	$R_{p0,2}$, MPa	R_m, MPa	A, %
HPDC, A380			
Ar rotary degassing	99	185	1.5
Ultrasonic degassing	104	181	1.1
LPDC, A356			
Ar rotary degassing	76	170	7.9
Ultrasonic degassing	76	173	9.0

4 Conclusions

From the results obtained in the present study the following conclusions can be inferred:

- Ultrasonic degassing performed using a single ultrasonic source and a prototype-level setup is able to achieve similar quality of the cast components as a mature, commercially available Ar-rotary degasser for an appreciable melt volume of up to 150 kg.
- The melt surface is much less disturbed during ultrasonic degassing, as cavitation bubbles are formed within the metal and the flow is directed downwards. As a result, much less dross formation is observed as compared to the Ar rotary degassing.
- The amounts of porosity in the cast components after both tested degassing technologies are similar with the tendency to form finer pores in the case of ultrasonic degassing.
- Mechanical properties of castings produced after either ultrasonic degassing or Ar rotary degassing are similar in two different casting processes (HPDC and LPDC) and two different casting alloys (AlSi9Cu3Fe (A380) and AlSi7Mg0.3 (A356)).

The authors would like to acknowledge the financial support provided by the European Union's Seventh Framework Program managed by REA – Research Executive Agency (FP7/2007-2013) under Grant Agreement number 286344 (www.ultragassing.eu). The authors gratefully acknowledge all help provided by the members of the consortium.

T. Pabel and T. Petkov, Austrian Foundry Research Institute, 8700 Leoben, Austria, M. da Silva, ASCAMM Technology Centre, Cerdanyola del Vallès, 08290, Spain / Universitat Autonòma de Barcelona, Cerdanyola del Vallès, 08193, Spain, R. Ruzsinszki, Certa Kft., Sátoraljaújhely, 3980, Hungary, X. Planta, Ultrasion, S.L., Cerdanyola del Vallès, 08290, Spain, J. Tort, Hornos y Metales, S.A., Ajalvir, 28864, Spain, D. Eskin, Brunel University, Brunel Centre for Advanced Solidification Technology, Uxbridge, UB8 3PH, United Kingdom / Tomsk State University, Tomsk, 634050, Russian Federation

Literature

[1] Campbell, J.: Castings. Butterworth-Heinemann, Oxford, 2003.

[2] Makarov, G. S.: Cleaning of aluminium alloys with gases. Moscow, Metallurgiya, 1983.

[3] Le Brun, P.: In: Light Metals 2002 (W. Schneider ed.). Warrendale, TMS, 2002. Pp. 869-875.

[4] Eskin, D.; Alba-Baena, N.; Pabel, T.; da Silva, M.: Mater. Sci. Technol. (2015), vol. 31, pp. 79-84.

[5] Eskin, G. I.; Eskin, D. G.: Ultrasonic treatment of light alloy melts. Second Ed., Boca Raton, CRC Press, 2014.

[6] Esmarch, W.; Rommel, T.; Benther, K.: Werkstoff Sonderheft. W. V. Siemens Werke, Berlin, 1940. Pp. 78-87.

[7] Bradfield, G.: Proc. Phys. Soc. B 63 (1950), pp. 305-321.

[8] Eisenreich, H.: Die Technik 5 (1950), pp. 310-315.

[9] Sergeev, S. V.: Physical and chemical properties of liquid metals. Moscow, Oborongiz, 1952.

[10] Kapustina, O. A.: Degassing of liquids. In: Physical principles of ultrasonic technology (L. D. Rozenberg ed.). Moscow, Nauka, 1970. Pp. 253-336.

[11] Eskin, G. I.: Ultrasonic treatment of molten aluminum. Moscow, Metallurgiya, 1965.

[12] Eskin, G. I.: Ultrason. Sonochem. 2 (1995), pp. 137-141.

[13] Altman, M. B.; Vinogradova, D. V.; Slotin, V. I.; Eskin, G. I.: Izv. Akad. Nauk SSSR, Otd. Tekhn. Nauk 9 (1958), pp. 25-30.

[14] Eskin, G. I.: Ultrasonic tretament of light alloy melts. Amsterdam, Gordon and Breach OPA, 1998.

[15] Davies, J. R. (ed).: Aluminum and aluminum alloys. ASM specialty book, Materials Park, ASM International, 1993. Pp. 201-204.

[16] da Silva, M.; Rebolledo, L.; Pabel, T.; Petkov, T.; Planta, X.; Tort, J.; Eskin, D.: Int. J. Cast Metals. Res. (2015) (accepted).

[17] Campbell. J.: Complete casting handbook. Butterworth-Heinemann, Oxford, 2011. Pp. 893-896.

Keywords: Ultrasonic treatment, aluminium alloy, degassing, casting, solidification, hydrogen, tomography, ultragassing