A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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# PHYSICAL MODEL OF THE BARBOTAGE PROCESS OF ALUMINIUM

# MODEL FIZYCZNY PROCESU BARBOTAŻU ALUMINIUM

The high quality of aluminium and its alloys is one of the most important aims of today's aluminium industry. This aim can be reached by refining process, especially barbotage. Knowledge about the mechanism of this process is very helpful to improve it. Refining is dependable on some processing parameters like: the flow rate of refining gas and the speed of the impeller. These parameters influence the shape and size of gas bubbles. There are four patterns of dispersion of the gas bubbles in the liquid metal: no dispersion, minimum, intimate and uniform. The short characteristics of these schemes have been presented in this paper. The physical model was created to determinate the level of gas bubble dispersion in liquids. Research was done as an analogy of the process of argon dispersion or other inert gas in liquid aluminium. Research was carried out for changing parameters: the flow rate of refining gas: 0÷17.5 $dm^3$/min and the speed of impeller: 0–400 rpm. The fifth case of dispersion was found: over – dispersion. The range selection of the processing parameters value for these five schemes was done.

*Keywords*: aluminium, physical modelling, barbotage process

Wysoka jakość ciekłego aluminium i jego stopów to obecnie jeden z najważniejszych celów, które stawia sobie przemysł aluminiowy. Cel ten można zrealizować poprzez proces rafinacji, a w szczególności poprzez barbotaż. Znajomość mechanizmu procesu barbotażu jest pomocna w jego ulepszeniu. Proces rafinacji zależy od parametrów procesowych takich jak: szybkości przepływu gazu rafinującego oraz prędkość obrotów rotora. Parametry te wpływają bowiem na kształt i wielkość pęcherzyków gazowych. Stwierdzono istnienie czterech przypadków dyspersji pęcherzyków gazowych w ciekłym metalu: brak dyspersji, dyspersja minimalna, dokładna i równomierna, których krótka charakterystyka została przedstawiona w pracy. Przedstawiony w pracy fizyczny model procesu został stworzony w celu możliwości określania stopnia dyspersji pęcherzyków gazowych w ciekłym metalu. Przedstawiono badania przeprowadzone jako analogię procesu dyspersji argonu lub innego gazu obojętnego w ciekłym aluminium. Badania przeprowadzano zmieniając parametry: przepływu gazu w zakresie: 0÷17,5 $dm^3$/min i obrotów rotora w zakresie: 0–400 obr/min. Stwierdzono istnienie piątego przypadku dyspersji – dyspersji nadmiernej, podano również wartości parametrów procesowych dla tego przypadku.

## 1. Introduction

The importance of aluminium is still increasing. The causes are the following [1, 2, 3]:

– aluminium products are used in many different areas of industry: from foils for packages, through military to transport (trains, cars, planes, space shuttle),
– the biggest market of secondary aluminium from all basic metals,
– the wide variety of the wrought alloys with very good characteristic,
– economical and ecological effect connected with aluminium recycling,
– the simplicity of recycling methods.

In industrial conditions it is not possible to get liquid aluminium and casts without inclusions and impurities. So, it is very important today to improve the quality of liquid metals. This can be reached by aluminium refining.

Both: the primary aluminium (electrolytic) and secondary one (after recycling) have many inclusions and gas bubbles (Table 1). So the main aim of the refining process is to remove three different kinds of undesirable impurities [4]:

- soluble hydrogen,
- soluble solid parts,
- soluble trace elements.

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The division of the refining methods used in industry are presented in Table 2. Nowadays one of the most popular methods of the aluminium refining process and its alloys is barbotage (bubbling inert gas).

TABLE 1

The impurities of the liquid aluminium [4]

| | Primary aluminium | Secondary aluminium |
|---|---|---|
| 1 | 2 | 3 |
| Contens | ≥99.7% Al | alloys |
| Hydrogen | 0.1÷0.3 ppm | 0.2÷0.6 ppm |
| Na | 30÷150 ppm | ≤10 ppm |
| Ca | 2÷5 ppm | 5÷40 ppm |
| Li | 0÷20 ppm | <1 ppm |
| Inclusions | $Al_4C_3$ | $Al_2O_3$, MgO, $MgAl_2O_4$, $Al_4C_3$, $TiB_2$ |

TABLE 2

The division of the refining methods [5]

| Refining methods | | Characteristic |
|---|---|---|
| 1 | | 2 |
| physics | segregation | use the influence of physical conditions (temperature, presure, move of metal) on the disturbance of the absorption equilibrium |
| | termic | |
| | extraction | |
| | vacuum extraction | |
| | bubbling inert gases | |
| | mechanical, filtration | |
| chemical | slag one | base on the chemical reactions between substances getting into metal with impurities |
| | gas one | |
| | slag and gas one | |
| | compilated | |

## 2. The hydrodynamic of the barbotage process

The most effective way to remove hydrogen from liquid aluminium is to insert tiny gas bubbles (they can not contain the hydrogen) to the metal many. These bubbles absorb hydrogen from liquid metals and remove it from that system. Particles (that are nonwettable by aluminium) are also removed, mainly by flotation caused by the same tiny bubbles.

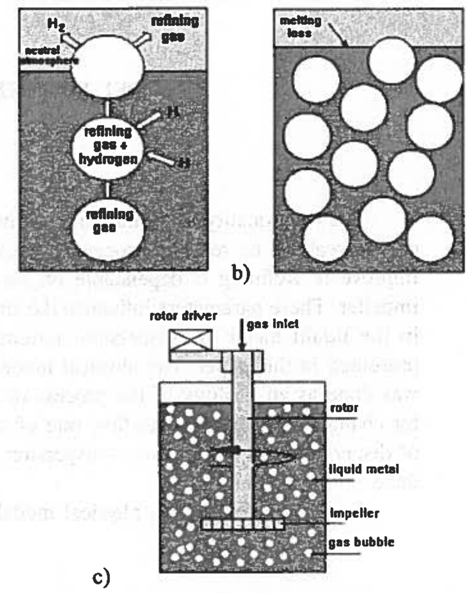



Fig. 1. The scheme of: a) the process of hydrogen removal from aluminium, b) the process of flotation the nonwettable particles to melting loss, c) the refining reactor with rotor [4]

TABLE 3

The review of the refining reactor with rotors used nowadays in word aluminium industry [6]

| Process | Company | Gas |
|---|---|---|
| 1 | 2 | 3 |
| Gas Injection Fluxing System GIFS | Noranda Technology Centre | Ar + $Cl_2$ |
| Ardal og Sundnal Verk – ASV | Ardal og Sundnal Verk | Ar |
| GBF | Showa Aluminium | Ar |
| Rapid Degassing Unit – RDU | FOSECO | Ar, Ar + $Cl_2$ |
| Spinning Nozzle Inert Flotation – SNIF | Union Carbide | Ar, $N_2$ |
| Aluminium Purification – Alpur | Aluminium Pechiney | Ar, Ar + $Cl_2$ |
| Alcoa 622 | Alcoa | Ar, $Cl_2$ |
| Alcan Filter Degasser – AFD | Alcan | Ar + $Cl_2$ |
| HYCAST | Hydro Metal Refining System | Ar + $Cl_2$ |
| Bath reaktor URO-200 | IMN – OML | Ar + $Cl_2$ |
| Rotoxal | Aluminium Martigny France | Ar |
| Shizunami | Nippon Light Metal Company | Ar |

Fig. 1 a) and 1 b) presents the scheme of hydrogen removal from liquid aluminium and flotation process [4]. The refining gas can be introduced to the liquid metal by lance, porous ceramic nozzle and rotor (rotating impeller). Typical refining reactor with rotor is presented in Fig. 1 c). In Table 3 the review of refining reactors (used nowadays in aluminium industry) is presented. The tiny gas bubbles and perfect characteristic of the mixing gas with metal can be reached in these reactors. The selection of the following parameters: the flow rate of refining gas and the speed of impeller is very important in this process.

The flow rate of refining gas influences the shape of gas bubbles and the process of their forming. Gas bubbles and drops of liquids which are moving in liquid phase have determined shape – shapes of gas bubbles are presented in Table 4. The equivalent gas bubble (if we take into consideration the moderate flow rate of refining gas for the bubbles with diameter in range 0.5 to 1.5 cm) is dependable only on the flow rate of refining gas. The influence of flow rate of refining gas on the gas bubble creation process is presented in Table 5 and shortly characterized.

In work [8] Oldshue presented four different flow patterns in liquid metals and their ratio of dispersion. The short characteristic of these patterns is presented in Table 6. In hydrogen removal process from liquid aluminium the gas bubbles generated in reactors with rotors can be uniformly dispersed in the whole metal. This can lead to low level of impurities and the shorter time of degassing.

TABLE 4

Shapes of gas bubbles and drops of liquids moving in liquid phase and their diameter

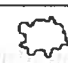
| Shape of bubbles | Diameter | Scheme |
|---|---|---|
| 1 | 2 | 3 |
| spherical | the diameter is very small: 0.5-0.7 cm |  |
| ellipsoidal | the diameter is in range: 0.8-1.0 cm |  |
| spherical cap | the diameter is higher than 1.0 cm |  |
| wobbling | if bubbles diameter is still increasing, shape of bubbles would be wobbling |  |

TABLE 5

The influence of flow rate of refining gas on the process of bubbles creation [7]

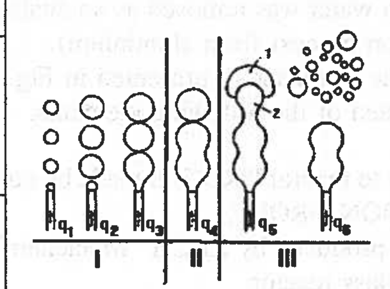
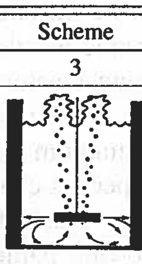
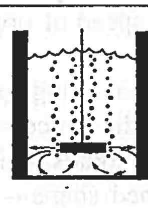
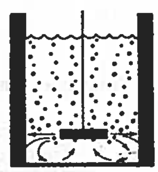
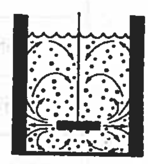
| Stage | Description | Scheme |
|---|---|---|
| 1 | 2 | 3 |
| I | there is free movement of gas bubbles |   |
| II | there is creation of bubbles chain, the space between bubbles disappeared and bubbles can be deformed, the film between bubbles is broken | |
| III | bubble 2 hit the bubble 1 and then their disintegration is observed, as a result the patch of bubbles with different diameters is created | |

TABLE 6

Flow model of gas bubbles in liquid metals, their ratio of dispersion and short characteristics

| Dispersion | Description | Scheme |
|---|---|---|
| 1 | 2 | 3 |
| no dispersion | the flow rate of refining gas is rather small, the speed of impeller is small too, therefore the gas bubbles generated by impeller rise up to the top of metal only along the shaft of impeller, there is almost a lack of mixing the gas bubbles with liquid metal |  |
| minimum | the flow rate of refining gas is small or moderate, the speed of impeller is medium, as a result the gas bubbles generated by impeller rise up to the top of metal with two streams along the shaft of impeller, there is only good level of mixing the gas bubbles with liquid metal in the middle part of reactor chamber |  |
| intimate | the flow rate of refining gas is moderate, the speed of impeller is high, this is why the level of mixing the gas bubbles generated by impeller with liquid metal is very good, there is lack of dispersion only at the side walls and below the rotating nozzle |  |
| uniform | the flow rate of refining gas is moderate, the speed of impeller is high or very high, therefore gas bubbles generated by impeller are very well mixed with liquid metal in whole volume of reactor, even below the nozzle of impeller |  |

## 3. Experimental work

The modeling research of the dispersion process of gas bubbles in liquids and the influence of the flow rate of refining gas and the speed of impeller on the rate of aluminium degassing process were carried out in the laboratory of Metallurgy Department in Silesian University of Technology in Katowice. The physical model of aluminium refining process by barbotage was designed (the oxygen soluble in water was removed as an analogy to hydrogen desorption process from aluminium).

The scheme of the test stand is presented in Fig. 2. This test stand consisted of the following elements:

- graphite impellers to reactor URO-200 made by company: SGL CARBON GROUP,
- rotameter Rln-06 produced by ZACH "Metachem",
- transparent plexiglass reactor,
- thyristor frequency converter TPC-1,5 made by Elmont company,
- compressor made by LEMATEK company.

The results of the research were recorded by digital camera Kodak CX6330.

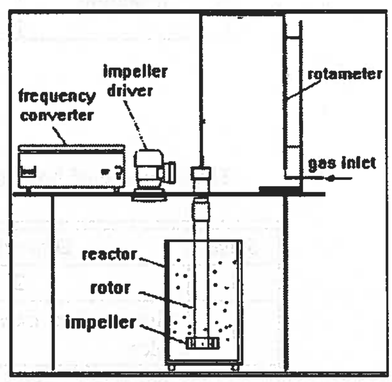
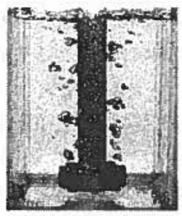
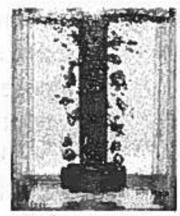
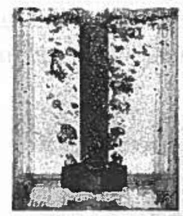
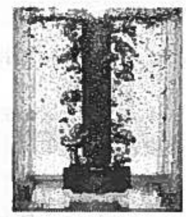
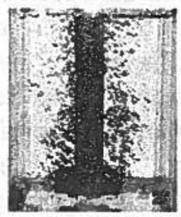
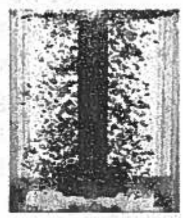
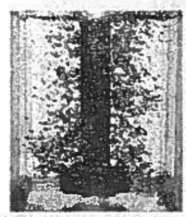
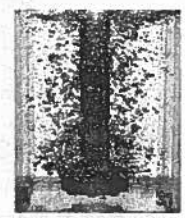
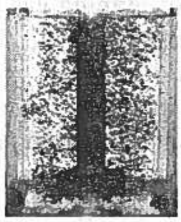
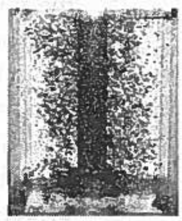
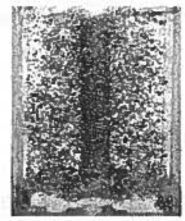
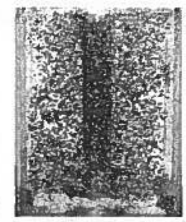
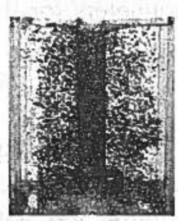
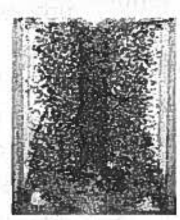
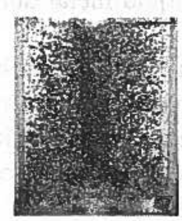
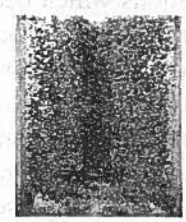
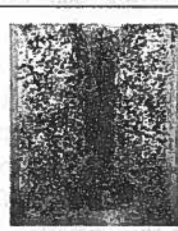
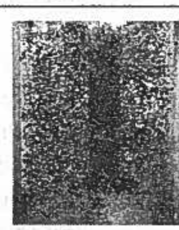
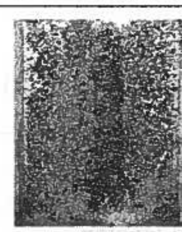
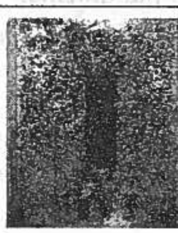
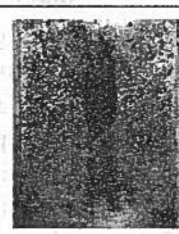



Fig. 2. The scheme of the test stand [9]

The main element of this system was impeller (the rotating nozzle). The impeller was submerged in transparent plexiglass reactor. The rotating nozzle was found 4 cm under the bottom of the reactor. The height of the column of water was 0.45 m. The air was getting to the nozzle from compressor. The flow rate of refining gas was measured by rotameter calibrated for the air in range: 0-1.2 $m^3/h$. The research was carried out for flow rate of refining gas in range: 0-17.5 $dm^3/min$. The conversion factor was the following: $1 m^3/h = 16.67$ $dm^3/min$.

TABLE 7

Research results of dispersion process of gas bubbles in liquids

| Impeller spped | The flow rate of refining gas | | | |
|---|---|---|---|---|
| | 5.0 dm$^3$/min | 10.0 dm$^3$/min | 15.0 dm$^3$/min | 17.5 dm$^3$/min |
| 0 rpm |  |  |  |  |
| 100 rpm |  |  |  |  |
| 150 rpm |  |  |  |  |
| 200 rpm |  |  |  |  |
| 300 rpm |  |  |  |  |
| 400 rpm |  |  |  |  |

Frequency converter which was installed in the system let to regulate the speed of impeller. This fact is connected with calculating the frequency of this converter to the speed of impeller. That was done by synchronizing the speed of impeller to the frequency of the flash of the stroboscopic tube. The conversion factor was the following: 1rpm = 10 Hz.

Pictures were taken for the following flow rate of refining gas: 0; 2.5; 5; 7.5; 10; 12.5; 15; 17.5 dm$^3$/min. For each of these flow rate the speed of impeller was changed in range: 0–400 rpm. The value of the change was 25 rpm every time. Research results are presented in Table 7. As the representatives, four values of flow rate: 5, 10, 15, 17,5 $dm^3$/min and the speed of impellers: 0, 100, 150, 200, 300 and 400 rpm were taken into account. Fig. 3 shows the case where the flow rate of refining gas is 0 $dm^3$/min and there is no rotating of impellers.

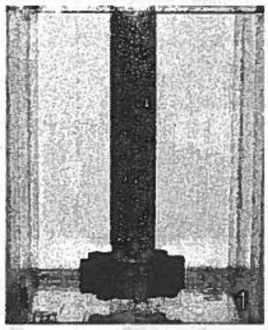


Fig. 3. The reactor chamber seen in case when there is no rotating of impeller and the flow rate of refining gas is 0 $dm^3$/min

## 4. Discussion

Physical model presented in work can simulate the conditions which occur in liquid metal during the refining process by barbotage.

Table 8 presents the condition of similarity between removal the oxygen soluble in water blowing by the air in room temperature and the liquid metals with the soluble hydrogen blowing by the argon. The area of refining gas bubbles can be presented as a function of the following parameters:

$$A = f\,(L,\ n,\ \rho_c,\ \rho_g,\ \eta_c,\ \eta_g,\ \sigma) \qquad (1)$$

where: L – characteristic geometric size, n – rotary speed of impeller, $\rho_c$ – liquid density, $\rho_g$ – gas density, $\eta_c$ – liquid dynamic viscosity, $\eta_g$ – gas dynamic viscosity, $\sigma$ – surface tension.

In the theory of process similarity which can be used in modeling research the equation (1) is treated as the base to the dimensional analysis. As a result we can obtain criterial number which characterized the phenomenon and give us opportunity to relate experiment data with analytic equations (Table 8). Described in references [14–17] cases of modeling research the refining reactors are fulfill by the water. Thus presented in this work physical model base also on water.

The level of rate of gas bubble dispersion in liquid metal was recorded by digital camera taking into consideration the process parameters. In Table 9 main information of three cases of dispersion: no dispersion, minimum dispersion and intimate dispersion was juxtaposed. Basing on Table 7 the range of values of flow rate of refining gas and speed of impellers was chosen for these kinds of dispersion and it was presented in Table 9. The short explanation is needed: the determined value of flow rate and the speed of impeller give the specific kind of dispersion, if these parameters are connected in the cross that means the lowest value of inert gas with the highest value the impeller speed.

The main information of the case of uniform dispersion (the most desirable in refining process) was juxtaposed in Table 10. The range of values of parameters: the flow rate of refining gas and the speed of impeller is also presented in Table 10. Research which was carried out let us claim that the existence of fifth case is also possible. It happens when the gas bubbles are too well mixed with liquid metal (there are many swirls) and then the undesirable chain of bubbles is created. This case of dispersion is characterized in Table 10. The range of processing parameters for this case is also presented in Table 10.

The fifth case which can be called over dispersion takes place when the value of flow rate of refining gas is high and the speed of impeller is very high. So high values of processing parameters caused that the level of mixing the refining gas with the liquid metal is very good, but swirls can be created and the probability of the existence of the chain of gas bubbles is very high (Table 5, column 3, interval III). There is also possible that the uniform dispersion can be changed into the intimate or the mixing the gas bubble with liquid metal can only happen in some parts of the reactor especially in the middle part of the impeller. There can be no more good mixing bubbles with metal at the side wall especially in the middle and upper parts.

Table 11 presents the equation [18] which give us opportunity of removal hydrogen quantitative determinations. In this Table some calculation concerning the AlSi7Mg alloys refining process are give as a example.

TABLE 8

The conditions of similarity between removal the oxygen soluble in water blowing by the air in room temperature and the liquid metals with the soluble hydrogen blowing by the argon [10–14]

| | | | |
|---|---|---|---|
| Liquid properties | Liquid | Water | Aluminium |
| | Temperature T, K | 293 | 973 |
| | Dynamic viscosity η, $Ns/m^2$ | 0.00101 | 0.00100 |
| | Surface tension σ, N/m | 0.072 | 0.680 |
| | Density $\rho_c$, $kg/m^3$ | 1000 | 2400 |
| Criterial number | Reynolds number: $Re = vL\rho_c/\eta_c$ (ratio of inertial forces to friction forces) | 27802 | 67392 |
| | Froud number: $Fr = vL/g$ (influence of liquid swirl – creation of funnel) | 0.0029 | 0.0029 |
| | Weber number: $We = v^2L\rho_c/\sigma$ (ratio of inertial forces to surface tension forces) | 84.24 | 21.41 |
| where: L – impeller diameter (d = 0.13 m), n – rotation speed (n = 200 rpm), v – linear speed v = n·r, r – distance from rotation ox | | | |

TABLE 9

The main information of three types of dispersion: no, minimum and intimate one

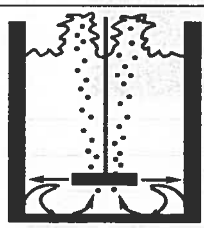
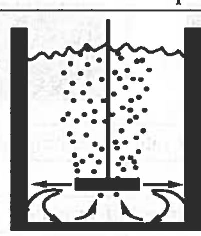
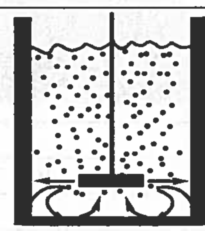
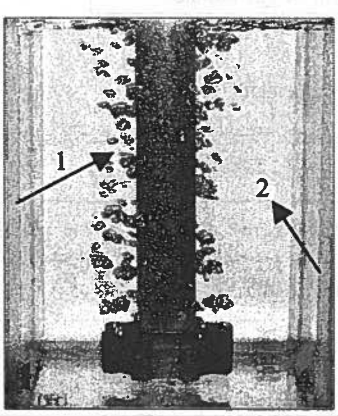
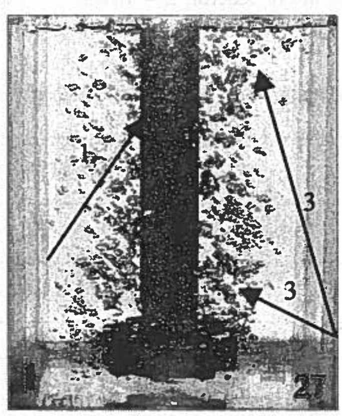
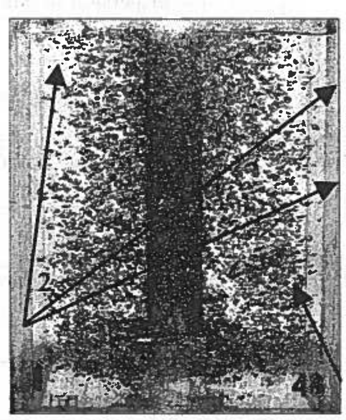
| No dispersion | Minimum dispersion | Intimate dispersion |
|---|---|---|
| 1 | 2 | 3 |
| The scheme of dispersion | | |
|  |  |  |
| Water model | | |
|   |   |   |
| The flow rate of refining gas | | |
| 0–10 $dm^3/min$ | 2.5–17.5 $dm^3/min$ | 2.5–17.5 $dm^3/min$ |
| The speed of impeller | | |
| 0÷50 rpm | 0÷100 rpm | 125÷300 rpm |
| 1 – bubbles which rise up along the shaft of impeller, 2 – no dispersion, 3 – partial dispersion, 4 – intimate dispersion | | |

TABLE 10

The description of dispersion: uniform and over dispersion

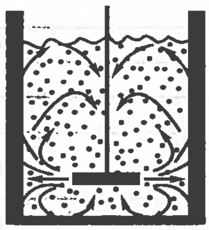
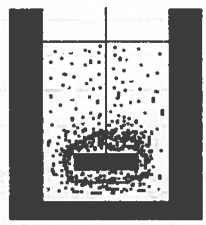
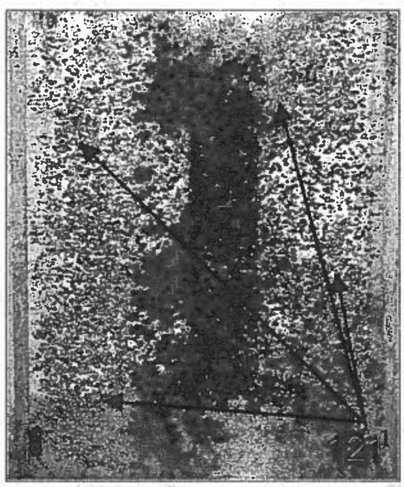
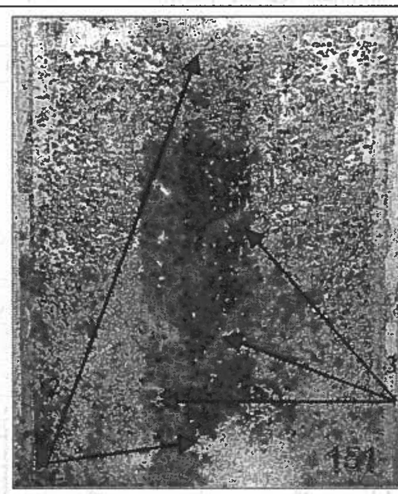
| Uniform dispersion | Over dispersion |
|---|---|
| 1 | 2 |
| Scheme | |
|  |  |
| Water model | |
|  |  |
| The flow rate of refining gas | |
| 10–17.5 $dm^3/min$ | 15–17.5 $dm^3/min$ |
| The speed of impeller | |
| 175–350 rpm | 325–400 rpm |
| 1 – dispersion in whole volume of reactor, 2 – swirls, 3 – the chain of gas bubbles | |

TABLE 11

Equation for quantitative determination of removal hydrogen and some calculations

| | | | |
|---|---|---|---|
| Equation for guantitative determination of removal hydrogen | $\frac{c_t}{c_i} = \exp\left(-0.011 \cdot \frac{\rho_c \cdot h}{M} \cdot \exp\left(-\frac{2969.16}{T}\right) \cdot d_e^{-1.75} \cdot V\right)$ | | |
| Processing parameters of AlSi7Mg refining | M = 300 kg, h = 0.45 m, $\rho_c$ = 2352.2 $kg/m^3$, T = 993 K, t = 10 min | | |
| Equation for determination of removal hydrogen from AlSi7Mg alloy | $\frac{c_t}{c_i} = \exp(-0.00197 \cdot d_e^{-1.75} \cdot V)$ | | |
| Modeling calculations | | | |
| Flow rate of refining gas q, $dm^3/min$ | 10 | 15 | 20 |
| Volume of gas V (V = qt = const), $m^3$ | 0.1002 | 0.1500 | 0.2040 |
| Equivalent diameter of gas bubble $d_e$, m | 0.0060 | 0.0083 | 0.0104 |
| Level of hydrogen removal $c_t/c_i$ | 0.217 | 0.274 | 0.305 |
| where: $c_i$ – initial hydrogen concentration, $c_t$ – final hydrogen concentration, h – height of liquid metal, M – mass of liquid aluminium, T – process temperature, t – refining time | | | |

## 5. Conclusions

On the basis of the research which was carried out the following conclusions were drawn:

- the flow rate of refining gas influence the shape of gas bubbles, the right selection of parameters: the flow rate of refining gas and the speed of impeller give us tiny gas bubbles mixed with liquid metal uniformly,
- there are four patterns of gas dispersion in liquid metal: no dispersion, minimum dispersion, intimate and uniform ones, the existence of fifth case of dispersion called over dispersion is stated, its characteristics are: swirls and undesirable chain of gas bubbles,
- the results of carried research let us select the processing parameters (the flow rate of refining gas and the speed of impeller) for each case of dispersion – they are juxtaposed in Table 12, these values give us particular case of dispersion if we cross for example the smallest value of the flow rate of refining gas with the highest value of the speed of impeller,
- optimal processing parameters of refining process (that means parameters which give us the uniform dispersion without the need of crossing these parameters) can be in range:
  - the flow rate of refining gas: 10–15 $dm^3$/min,
  - the speed of impeller: 150–250 rpm,

  higher flow rate needs more refining gas and this is connected with the increasing cost of the refining process and there is also the high probability of the chain flow of refining gas existence, especially if the speed of impeller is very high. That is why the refining gas is not uniformly mixed with the liquid metal and the swirls are created, so the over dispersion is possible.

TABLE 12

The processing parameters of aluminium refining versus the dispersion of the gas bubble

| Dispersion | No dispersion | Minimum | Intimate | Uniform | Over dispersion |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| flow rate of refining gas, $dm^3$/min | 0–10 | 0–15 | 2.5–17.5 | 10–17.5 | 15–17.5 |
| speed of impeller, rpm | 0–50 | 0–100 | 125–300 | 150–350 | 325–400 |

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