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COMPLEX OF MATHEMATICAL MODELS AND METHODS TO CALCULATE PRESSURE EFFECT ON SULFIDE DISTRIBUTION IN STEEL

Primary objective is to develop computational method to analyze digital pictures of sulfide prints, helping obtain qualitative image characteristics, and to formulate mathematical model of the distribution of sulphide inclusions to determine specific features of the pressure effect on the macrostructure formation of carbon steel castings flooded into the uncooled mold.

The research was carried out using images of sulfide prints of templates cut of steel cylindrical castings; L500 steel was applied. The castings result from industrial tests of a method of gas-dynamic effect on the fusion in the foundry forms under the conditions of a casthouse of Dnipropetrovsk aggregate plant PJSC. Digital pictures of sulfide prints, obtained in terms of the increased rate of gas pressure and maximum pressure, were binarized; defective fra gments were removed; and zoning took place. The developed computational method has been applied for fragments of images, representing different zones; data arrays have been received containing sizes and amounts of inclusions in the fragment.

The developed computational method to analyze digital images of sulfide prints has been implemented. ASImprints software support has helped obtain qualitative characteristics of images; namely, distribution of amount of the certain-size sulfide inclusions.

The computational method to analyze digital images of sulfide prints has made it possible to study the set of patterns of sulfide prints. The dependences have been obtained, describing specific features of sulfide inclusion distribution while varying gas-dynamic pressure method in terms of fusion in the casting form. It has been demonstrated that the distribution describes effectively the power-series distribution to compare with the exponential one. Mathematical model of the power-series distribution parameter dependence upon pressure has been developed. Deviation of the distribution parameters in terms of the experimental values and the model values has been evaluated.

The research demonstrates the ways to apply an algorithm of simple recursive casting for quantitative analysis of digital images of sulfide prints. Use of ASImprints, being software implementation of the computational method to analyze digital images of sulfide prints making it possible to obtain qualitative characteristics of images, has helped identify that the increased pressure within a casting-device for gas injection system results in the increased specific amount of inclusions and the decreased specific zone of sulfide inclusions respectively. It has been defined that exponential function describes reliably the nature of sulfide inclusion distribution in the digital image of sulfide print. The research has demonstrated that fragments of a sulfide print, belonging to one zone, are statistically homogeneous. Thus, it is possible to analyze quantitively digital image zone of a sulfide print on its fragment. Mathematical model of dependence of sulfide inclusion distribution in carbon-steel castings in terms of gas-dynamic effect on fusion solidifying in a mold has been developed. The model may be applied to predict sulfide inclusion distribution within the selected zones of cross section of the cylindrical castings solidifying in the uncooled mold in terms of the preset mode of gas-dynamic effect.

Keywords: gas-dynamic effect, pressure, solidification, casting, steel, 35 Л, mold, macrostructure, sulfides, inclusions, template, sulfide print, distribution, polynomial, parameters, prediction, software implementation, ASImprints

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КОМПЛЕКС МАТЕМАТИЧНИХ МОДЕЛЕЙ ТА ОБЧИСЛЮВАЛЬНИХ МЕТОДІВ ДЛЯ ВИЗНАЧЕННЯ ВПЛИВУ ТИСКУ НА РОЗПОДІЛ СУЛЬФІДІВ В СТАЛІ

Розробка обчислювального методу для аналізу цифрових зображень сірчаних відбитків, що дозволяє отримувати кількісні характеристики зображень. Розробка математичної моделі параметрів розподілу сульфідних включень для визначення особливостей впливу тиском на формування макроструктури виливків із вуглецевої сталі, що заливаються в неохолоджуваний кокіль.

Дослідження проводились на цифрових зображеннях сірчаних відбитків темплетів, що вирізані із сталевих виливків циліндричної форми із сталі 35Л. Виливки були отримані в ході промислових випробувань технології газодинамічного впливу на розплав в ливарній формі в умовах ливарного цеху ПАТ «Дніпропетровський агрегатний завод». Цифрові зображення сірчаних відбитків, що отримані при варіації швидкості наростання газового тиску та максимального тиску, бінарізували, видаляли дефектні фрагменти, розділяли на зони. Для фрагментів зображень, що представляли різні зони, був застосований розроблений обчислювальний метод, отримані масиви даних, що містять розміри та кількості включень в фрагменті.

Розроблений обчислювальний метод аналізу цифрових зображень сірчаних відбитків було програмно реалізовано. Програмна реалізація «ASImprints» дозволяє отримувати кількісні характеристики зображень, а саме розподіл кількості сульфідних включень певного розміру.

Застосування обчислювального методу аналізу цифрових зображень сірчаних відбитків дозволило провести дослідження серії зображень сірчаних відбитків. Отримані залежності, що описують особливості розподілу сульфідних включені при варіації технології газодинамічного тиску на розплав в ливарній формі. Показано що даний розподіл вдало описує ступеневийй розподіл у порівнянні з експоненційним. Отримана математична модель залежності параметрів ступеневого розподілу від тиску. Проведена оцінка відхилення параметрів розподілу експериментальних та модельних значень.

В роботі показані шляхи використання алгоритму простої рекурсивної заливки для кількісного аналізу цифрових зображень сірчаних відбитків. Застосування «ASImprints» – програмної реалізації обчислювального методу для аналізу цифрових зображень сірчаних відбитків, що дозволяє отримувати кількісні характеристики зображень, надало можливість визначити, що збільшення тиску в системі виливок-пристрій для введення газу призводить до збільшення питомої кількості *включень, і відповідного зменшення питомої площі сульфідних включень. Встановлено, що характер розподілу сульфідних включень на цифровому зображенні сірчаного відбитка достовірно описується ступеневою функцією. Проведені дослідження показали, що фрагменти сірчаного відбитка, які належать одній зоні, є статистично однорідними. З цього випливає, що можливе проведення кількісного аналізу зони цифрового зображення сірчаного відбитка по його фрагменту. Отримано математичну модель залежності функції розподілу сульфідних включень в литих заготовках із вуглецевої сталі при газодинамічному впливі на розплав, що твердіє в кокілі. Модель може бути застосована для прогнозу розподілу сульфідних включень в обраних зонах поперечного перетину даного циліндричного виливка, що твердіє в неохолоджуваному кокілі, при заданому режимі газодинамічного впливу.*

Ключові слова: газодинамічний вплив, тиск, твердіння, виливок, сталь, 35 Л, кокіль, макроструктура, сульфіди, включення, темплет, сірчаний відбиток, розподіл, ступеневий, параметри, прогноз, програмна реалізація, «ASImprints».

Introduction

Solidification process is characterized by the progress of chemical nonhomogeneity and formation of different defect types, which amount and distribution is determined with the help of casting quality [1]. It concerns sulfide inclusions in steel to the fullest extent [2][3]. That is why specific attention is paid to new methods minimizing negative effect of the inclusions [4][5]. Among other things, the methods are based upon the external physical effect on the solidification process. A method of gas-dynamic effect on the fusion in a casting form; modification [6][7]; vibration effect [8][9]; and ultrasound [10][11] are among them. It has been established that modification of the AK7ch alloy results in the uniform distribution of eutectics (α-Al β-Si) and structural components, diminishing silicon crystals by a factor of 1.5–2.0 on average, refining, and variation in shape of Fe-containing phases [12]. It is established that the decrease of crystallinity after modification is related to the general refinement of the microstructure [13].

Research [14][15] describes the developed operating schedules of the combined action on fusion during crystallization in a cooling form. The results of the experiments and industrial tests, concerning analysis of the efficiency of ultra- and nanodisperse inoculants obtained by means of a method of plasma chemical synthesis, have demonstrated 15-45% increase in useful life of details of metallurgical equipment produced from complex alloyed and inoculated foundry goods [16][17]. Gas-dynamic pressure and modification with the help of ceramic nanoparts are the alternative approaches to improve characteristics of metals and alloys [18][19].

The method of gas-dynamic pressure (effect) on the fusion in a casting form, described by Ukrainian patent 55301, is implemented using gas pressure within 0.1-20 MPa range mainly. No complex specific equipment is involved; thus, it can be added easily to the current operating schedule. However, determination of efficiency of the gas-dynamic effect on a fusion under solidification needs study of numerous different factors. Particularly, it concerns physiochemical parameters of cast metal where structure and phase composition are among the most important ones [20][21]. Laboratory tests of macro- and microstructure as well as physical and mechanical characteristics of casting metal, obtained directly under industrial conditions with the use of both traditional and the developed methods, have demonstrated significant efficiency of the proposed operating schedules. Taking into consideration the necessity to obtain individual operating parameters for the implementation of certain alternative of the proposed process in terms of specific casting or ingot, it becomes quite important to develop a complex of mathematical models and computational methods to provide reliable simulation, evaluation, and determination of rational modes of effect [22] on the structure formation and mechanical characteristics of casting metal by the controlled gas pressure [23].

Related works

Paper [24] analyses mathematical models describing a process of a casting metal solidification. Certain disadvantages of Fourier-Kirchhoff equation use within a set with Navier-Stokes equation to predict quantitative characteristics of shrinkage defects have been shown. Criterion approach to evaluate localization and shrinkage fissuring parameters has been considered. It has been demonstrated that maximum reliable prediction of shrinkage defects can be implemented taking into consideration mass redistribution connected with the dependence of thermophysical parameters upon the final volume conditions. A correct mathematical model of a phase transition, involving thermal, convectional, and filtration processes in a two-phase zone [25], should take into consideration specific features of the physical processes following a process of the two-phase zone supply.

It is known that at a room temperature, sulfide solvency in austenite and ferrite is minor. In this context, almost all sulfide, containing in steel, is in the form of sulfides. Characteristics of steel depend upon the amount of sulfides (sulfide content) as well as upon their sizes, shape, and distribution. If sulfide concentration in lithium medium-carbon steel varies from 0.02 to 0.06% then relative narrowing drops from 53-62 down to 20-47%; toughness drops from 0.8-1.1 down to 0.4-0.5 MJ/m2 during Charpy impact tests [26]. According to [27][28], the increased sulfide content in lithium steel (0.24% C, 1.07% Mn, 1.29% Si, and 0.0048% P) from 0.02 to 0.054 % decreases toughness more than twice. In terms of 30ХНМЛ steel, 0.016 % up to 0.12% increase in the sulfide content factors into the increased amount of sulfides as well as in their average size [26]. The increased steel contamination by sulfides results in the number of arising microfissures; their coalescence happens easier due to shortening distances between inclusions. The abovementioned stipulates the decrease in fissure expansion.

Authors of [26] have identified considerable dependence of plasticity and toughness upon sulfide type and distribution nature. Eutectic sulfides, being distributed within the boundaries of dendritic branches, generate the most negative effect on the mechanical characteristics; moreover, sulfide phase of eutectic has dendritic skeleton. Total length of the inclusions may vary significantly in terms of similar amount. Globular shape of sulfide inclusions can be considered as the most favourable one since minimum contamination index and maximum values of properties of steel correspond to it [26]. Paper [27] mentions that from the viewpoint of density and mechanical characteristics, disoriented irregular-shape inclusions, formed in steel, if residual aluminium is available (>0.020%), are optimal inclusions. Size of inclusions and their distribution is influenced heavily by the processes of deoxidation and modification using ferrocerium and other alloys with rare-earth elements. As a result, the improvement of mechanical characteristics of steel is noted [28]. Moreover, pressure, favouring uniform distribution of non-metal inclusions in castings, is one of the effective methods to effect fusion. For instance, their amount and size within the thermal centre of carbon-steel casting decrease in terms of Poisson extrusion and piston extrusion are lowered by 3.5 and 1.5 times respectively to compare with the castings produced with the help of traditional methods [29][30]. Research results, concerning mechanical characteristics of 35Л steel castings, obtained by means of the standard metal mold casting and with the use of gas-dynamic effect, also demonstrated favourable pressure effect on sizes of sulfide inclusions, and their distribution nature. Implementation of the method may help influence solidification process at the expense of the development of the controlled gas pressure within a casting-device for gas injection [21]. Thus, studies, intended to determine regularities of distribution of sulfide inclusions, their amount and sizes in cast steel (among other things, in terms of various modes of gas-dynamic modes) is a topical problem.

Currently, research is carried out connected with the modeling of thermal fields in casting to identify defects of filling and shrinkage [31][32]. Computing experiments are performed to study the effect of gas porosity on the mechanical characteristics of Al–Si alloys caused by the presence of the dissolved hydrogen [33]. A three-dimensional cellular automaton model was developed to predict the formation and evolution of hydrogen porosity coupled with grain growth during solidification of a ternary Al-7wt.%Si-0.3wt.%Mg alloy [34][35].

The research is intended to develop a complex of mathematical models and computational methods to identify specific features of pressure effect on the formation of inhomogeneity of sulfide inclusion distribution within the cylindrical castings made from 35Л steel flooded in the uncooled mold. Among other things, it concerns a mathematical model of dependence of sulfide inclusion size and amount for different zones of casting and gas-dynamic effect parameter intersection.

Description of the full-scale experiment

One of the industrial tests of the developed method of gas-dynamic effect on the fusion in a foundry form was carried out under the conditions of a casthouse of Dnipropetrovsk aggregate plant PJSC.

Steel of 35*Л* grade (GOST 977-88) was melted using induction furnace ICT-016 with acid lining. Pouring was performed right from the furnace into a steel single-piece metal mold with 100 mm average wall thickness, 550 mm height of a working space, and 240 mm average diameter.

Internal surface of the mold, heated up to 380-4000 C, was coated with disten-sillimanite-based parting mixture. Discharge temperature was 1640+50 C. Casting height was 370+5 mm. Weight was 160+2 kg.

Gas-dynamic effect was analyzed in terms of the varied velocity of argon pressure increase within a casting-device for gas injection system (V_P) and maximum pressure (P) indices according to following modes: melting 2 – Vp=0.0015 MPa/s, P=1MPa; melting 3 – Vp=0.0025 MPa/s, P=2 MPa; and melting 4 – Vp=0.004 MPa/s, P=3 MPa.

Characteristics of the melted metal (meltings 2-4) were analyzed as compared with the same grade steel produced with the help of a traditional method (melting 1).

After the cast section was removed from the mold, the former was cut to obtain proper templates.

There were obtained sulfide prints [36][37][38] of templates resulting from the experimental melting and the comparative melting (i.e. casting produced according to a traditional method).

Metal science understands a template as a test plate cut out from a metal product to study its structural properties. At a macrolevel, the obtained images reflect availability of inclusions while helping carry out further quantitative tests with the use of the current computational techniques and algorithms to understand the images and analyze them[39][40].

According to the results of sulfide liquation using a method of sulfide print on a photo paper (in terms of Baumann’s method) [41], the sulfide distribution (either uniform or nonuniform) is determined over a cross section of a template cut from the product. Among other things, nonuniform sulfide distribution stipulates significant inhomogeneity of distribution of mechanical characteristics of the cast metal intensifying the product destruction in the process of its operation.

Computational technique to determine quantitative characteristics of digital images of sulfide prints

The following may be considered as specific features of digital images of sulfide prints [23]:

– colour image gradation (gray shades);
– irregular shapes of the reduced brightness zones corresponding to sulfide inclusions;
– random nature of manifestation of zones with the reduced brightness;
– random size of zones with the reduced brightness; and
– limitless image size.

The specific features prevent from the use of the most popular methods analyzing digital images based upon their classification compared with a pattern [42][43]. Moreover, such a case is quite difficult for the application of neural-network methods of image analysis and identification since it is impossible to forecast volume of practice sampling as well as its composition to include the whole set of possible location and shapes of the reduced brightness zones corresponding to sulfide inclusions [44]. Thus, the topical research problems may involve the development of efficient computational and software tools for the quantitative analysis of digital images of sulfide prints which needs neither previous classification nor the use of master images.

The following is applied as quantitative characteristics of digital images of sulfide prints:

– specific zone of the inclusions (K_S, %)

$$K_S = \frac{S_{B\Phi}}{S_\Phi} 100\% , \quad (1)$$

where $S_{B\Phi}$ – zone of the inclusions in a fragment, mm2; S_Φ – the fragment zone, mm2;

– specific amount of the inclusions (KN, units/mm2)

$$K_N = \frac{N_{B\Phi}}{S_\Phi} , \quad (2)$$

where $N_{B\Phi}$ – amount of the inclusions in the fragment, units.

Analysis of computer graphics methods has shown the perspectiveness of the use of recursive casting to obtain quantitative characteristics of digital images of templates of castings [29, 30].

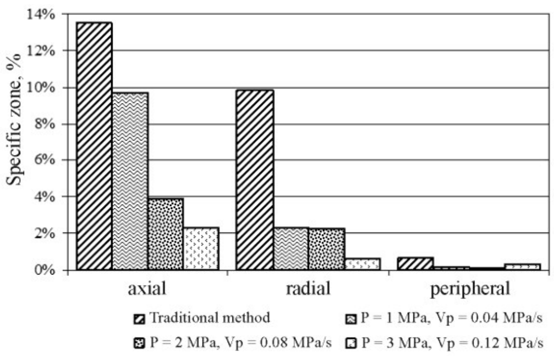
In general, the recursive casting algorithm is a following procedure. It is determined whether the pixel is coloured with the preset brightness threshold. If not, it is redyed. Then, four neighbouring ones are controlled; if it is necessary, they are redyed too. In this context, modification of the algorithm while introducing a counter of the coloured pixel amount covered by the boundary-limited zone makes it possible to define the less bright zone in terms of the specified image identification.

Programming tool (PT) ASImprints has been developed to perform quantitative analysis of sulfide prints. The tool implements the possibility to process grayscale as well as monochrome images of both entire sulfide prints and their fragments [45].

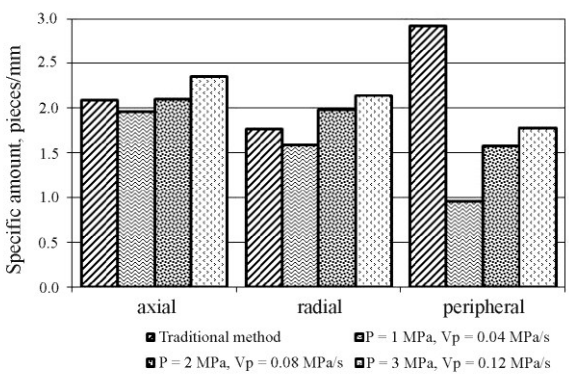
Analysis of sulfide prints of templates of metal by experimental and comparative melts using ASImprints tool

The obtained sulfide prints were analyzed according to a conditional division of a print zone into axial, radial, and peripheral zones basing upon the thermographic analysis of solidification process of the casting. It has been predicted that the distribution nature of sulfide inclusions is stable within each of the zones. Following values of width of the zones were taken up: 40 mm for the axial zone on the casting radius; 60 mm for the radial zone; and 20 mm for the peripheral one.

Then the sulfide prints were scanned with 300 dpi separative power; transformed into grayscale ones; and prepared them preliminarily while separating from the total zone of the scanned images of a zone corresponding directly to the sulfide print. Defect image fragments were excluded from the consideration with the help of their pouring. Expert evaluation helped determine binarization threshold for each image of the series. After that, the image fragments, corresponding to each of the zones, were selected. The considered fragments are of similar shape – a square of 15 mm side. Recursive casting algorithm has been applied for each fragment to identify amount and sizes of sulfide inclusions [46]. Then average size of a sulfide inclusion S cp was determined as well as specific zone of the inclusions (K_S, %), and specific amount of the inclusions using formulas (1,2).



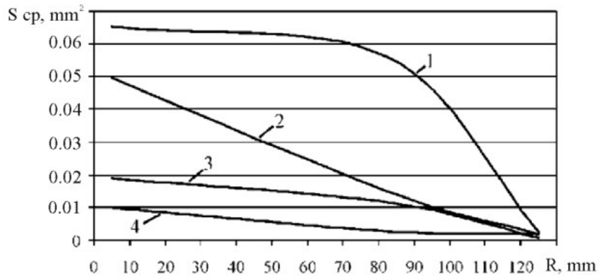
a)



b)

Fig. 1. Specific zone (a) and specific amount (b) of inclusions in different zones of casting templates obtained in terms of the traditional method and with the use of gas-dynamic effect on a casting in a mold

Rate of gas pressure increment and maximum pressure value within a casting-device for gas injection system have a pronounced effect on the uniformity of sulfide distribution within a casting cross section (Fig. 2).



1 – traditional method
2 – P = 1 MPa, Vp = 0.04 MPa/s
3 – P = 2 MPa, Vp = 0.08 MPa/s
4 – P = 3 MPa, Vp = 0.12 MPa/s

Fig. 2. Dependence of average size of sulfide inclusion upon the effect of gas-dynamic modey

Ratios between the average inclusion sizes within the axial, radial, and peripheral zones of casting templates obtained as a result of the traditional method (melting 1) and experimental methods (meltings 2-4) are: 1: 1.2: 28; 1: 3: 31; 1: 2: 25; 1: 4: 5 respectively (Fig. 12). In this context, increase in pressure up to 3 MPa results in the decrease of sulfide inclusion. Thus, casting experiences ~ 6.5 times decrease in axial zone; ~ 20.6 times decrease in radial zone; and ~ 1.2 times decrease in peripheral one.

Mathematical model of dependence of sulfide inclusion distribution in cylindrical carbon-steel casting in terms of gas-dynamic effect on fusion solidifying in a mold

It often happens that in the process of sulfide print production certain image share turns out to be defective; hence, it should be excluded from further quantitative analysis. Hence, it is required to make sure in homogeneity of sulfide inclusion distribution within the selected zones using monochromic digital images.

During the research, ten 10×10 mm fragments were separated from each zone of sulfide print. Value array, containing information on the inclusion sizes and amount, has been obtained. Graphs of the inclusion amount dependence upon the size have been constructed. The dependence is a descending function which can be approximated by means of power dependence or exponential one. It has been determined that power approximation is more accurate to describe distribution of sulfide inclusions for the fragments of images of sulfide prints of casting templates obtained in terms of the traditional method (Fig. 3) and with the use of gas-dynamic effect (Fig. 4).

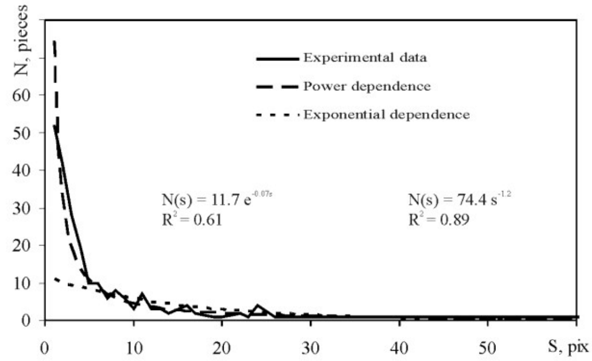


Fig. 3. Distribution of sulfide inclusions within the image fragment of sulfide print of axial zone of a casting template produced according to the traditional method

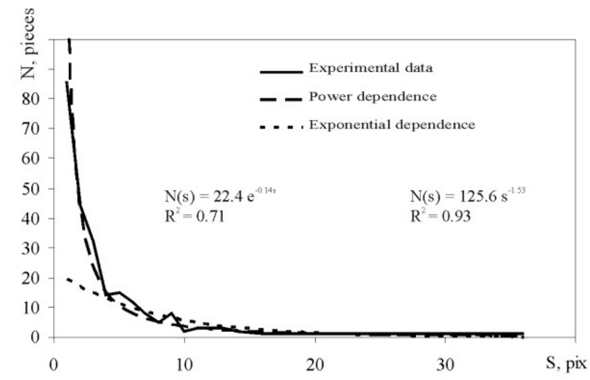


Fig. 4. Distribution of sulfide inclusions within the image fragment of sulfide print of radial zone of a casting template produced with the use of gas-dynamic effect: Vp = 0.12 MPa/s, P = 3 MPa

In terms of each of the considered fragments, a function of density of power distribution probability $N(s) = As^{\lambda}$ (if $s \geq 0$) has been obtained where A is the scaling ratio inversely related to the fragment zone and λ is the parameter of power distribution structure.

A and λ values of density of power distribution probability have been averaged; mean-square error within the image sampling of each zone has been calculated. The abovementioned characterizes probable deviation of average values of the considered parameters from their average value (Table 1).

Table 1

Mean-square error of power distribution parameters

Zone	Mean-square error, %	
	A	λ
Axial	12	5
Radial	8	7
Peripheral	6	3

Mean-square error for A and λ did not exceed 15% in terms of the fragments of each of the considered zones. That confirms statistic homogeneity of the fragments, belonging to one and the same zone as well as possibility to analyze quantitatively a zone of a digital image of sulfide print in terms of its fragment. Moreover, the carried out correlation analysis between the arrays of values of sizes and inclusion amount, corresponding to each of the ten images, and the averaged analytical dependence approximating them (Table 2) verified the conclusion.

Table 2

Correlation analysis results

Zone	Correlation coefficient									
	1	2	3	4	5	6	7	8	9	10
Axial	0.88	0.97	0.94	0.84	0.91	0.96	0.95	0.96	0.89	0.95
Radial	0.98	0.99	0.99	0.97	0.96	0.95	0.99	0.99	0.97	0.97
Peripheral	0.97	0.98	0.97	0.93	0.97	0.97	0.97	0.99	0.99	0.98

One fragment from each zone of sulfide print image has been selected to develop a mathematical model of dependence of the gas-dynamic effect, sizes, and amount of sulfide inclusions for different zones of the casting cross section. Shape of a fragment for each zone is a square which side size is not more than a width of peripheral (i.e. the narrowest) zone being 20 mm. The selected size of the fragment is 15 x 15 mm.

Use of the computer program ASImprints for digital images of sulfide prints of casting templates, obtained in terms of different modes of gas-dynamic effect, has helped form value arrays of the zones of inclusions as well as corresponding to them amount of inclusions for each selected zone. Parameters of density function of power distribution probability have been determined for each of the obtained arrays; as it has been demonstrated hereinbefore, that describes quite accurately the dependence of the amount of inclusions upon their size. Moreover, the fact is supported by the corresponding R^2 values (Table 3).

Table 3

Parameters of the mathematical model of the correlation between the amount of inclusions and their size (density of power distribution probability) and approximation accuracy

Melting	Zones of casting cross section								
	axial			radial			peripheral		
	A	λ	R^2	A	λ	R^2	A	λ	R2
1	59.2	-0.89	0.79	60.1	-0.91	0.83	288.0	-1.43	0.94
2	77.7	-0.96	0.82	148.2	-1.37	0.91	175.3	-2.03	0.88
3	127.6	-1.21	0.88	178.3	-1.39	0.88	337.0	-2.06	0.96
4	287.6	-1.54	0.91	335.2	-1.82	0.94	351.9	-2.20	0.97

Figures 5 and 6 demonstrate graphs of scaling ratio and structure of power distribution parameter dependence upon the gas-dynamic mode effect (first of all, pressure P, MPa). The dependences, obtained as a result of image fragment processing correspond to the unbroken lines with markers; dependences, approximated by a linear function belong to the dotted indexed lines:

1 – peripheral zone $A(P) = 23.58\ P + 282.12$. $R^2 = 0.93$. (4)

2 – radial zone $A(P) = 85.54\ P + 52.13$. $R^2 = 0.93$. (5)

3 – axial zone $A(P) = 73.52\ P + 27.73$. $R^2 = 0.84$; (6)

1 – peripheral zone $\lambda(P) = -0.25\ P - 1.51$. $R^2 = 0.93$. (7)

2 – radial zone $\lambda(P) = -0.28\ P - 0.96$. $R^2 = 0.91$. (8)

3 – axial zone $\lambda(P) = -0.22\ P - 0.82$. $R^2 = 0.93$. (9)

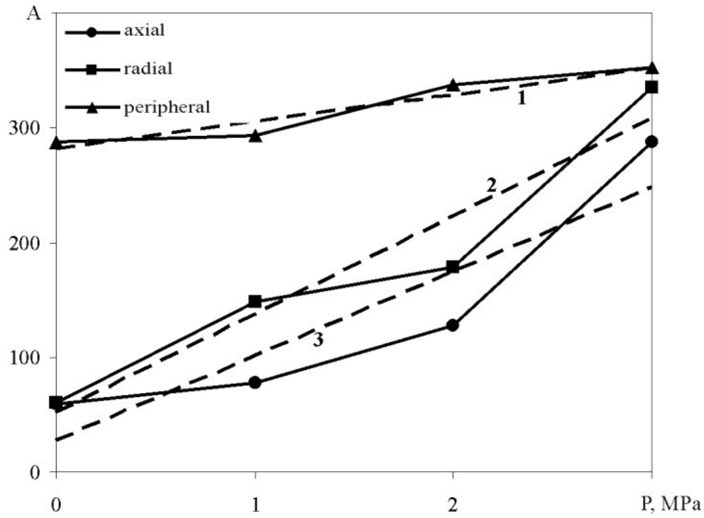


Fig. 5. Graph of scaling ratio of power distribution dependence upon the pressure in terms of gas-dynamic effect

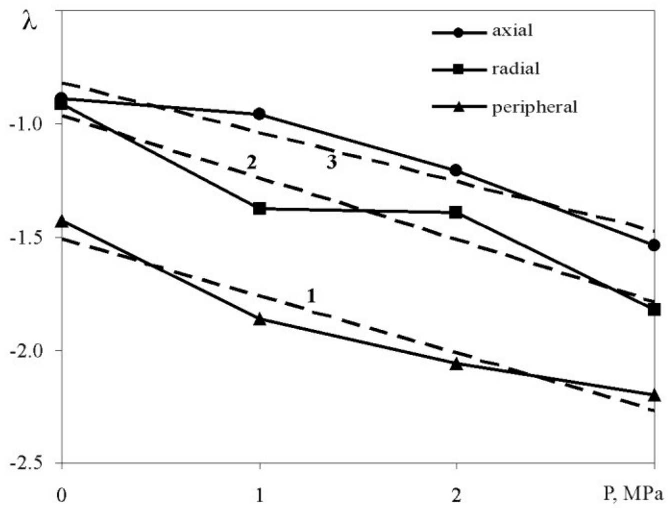


Fig. 6. Graph of a parameter of power distribution structure upon the pressure in terms of gas-dynamic effect

Approvement of the mathematical model of dependences of sulfide inclusion distribution in carbon-steel castings upon fusion, solidifying in a mold, in terms of gas-dynamic effect

The obtained mathematical models (4-9) make it possible to interpolate parameter values of the power distribution helping predict in such a way the sulfide inclusion distribution within the selected cross section zones of the cylindrical casting solidifying in the uncooled mold in terms of the specified gas-dynamic effect. Table 4 represents the comparative computational results of the specific inclusion amount (K_N, pieces/mm^2) in axial (A), radial (R), and peripheral (P) zones of sulfide print image.

Table 4

Specific amount of inclusions

Melting	Specific amount of inclusions, pieces/mm2								
	experiment			computations			deviations, %		
	cross section of the casting								
	A	R	P	A	R	P	A	R	P
1	2.08	1.77	0.96	2.28	2.09	1.16	10	18	21
2	1.96	1.59	0.96	2.24	1.84	1.11	14	16	16
3	2.10	1.98	1.58	2.48	2.03	1.85	18	3	17
4	2.35	2.15	1.78	2.79	2.52	2.13	19	17	20

The data, shown in Table 4, demonstrate such deviation level which does not exceed 20%; thus, accuracy is rather high. Hence, the mathematical model of dependences of sulfide inclusion distribution in carbon-steel castings upon fusion, solidifying in a mold, in terms of gas-dynamic effect is applicable while developing the considered operating schedule.

Conclusions

Possibility to use simple recursive casting for quantitative analysis of digital images of sulfide prints has been identified. It has been defined that introduction of a counter of the coloured pixel amount covered by the boundary-limited zone helps characterize less bright zones (i.e. sulfide inclusions) in terms of the specified image identification. ASImprints software support has been developed to process grayscale as well as monochrome images of both entire sulfide prints and their fragments.

Use of the developed computational method to determine quantitative characteristics of digital images of sulfur prints and its program implementation (i.e. ASImprints) have helped analyze quantitatively digital images of sulfur prints. It has been identified that the increased pressure within a casting-device for gas injection system results in the increased specific amount of inclusions and the decreased specific zone of sulfide inclusions respectively.

Analysis of the nature of sulfide inclusion distribution for fragments of images of sulfur prints of casting templates, obtained in terms of the traditional method and with the use of gas-dynamic effect, has shown that power function is the most accurate technique to describe the distribution. In this context, approximation reliability (R^2) is 0.89-0.95. Consequently, it has become possible to define statistical homogeneity of the fragments belonging to one and the same zone; the abovementioned has made it possible to analyze quantitively a zone of digital image of sulfide print in terms of its fragment.

Mathematical model of the dependence of sulfide inclusion distribution in carbon-steel castings in terms of gas-dynamic effect on fusion solidifying in a mold has been developed. The model relies upon interpolation of the parameter values of power distribution making it possible to predict the distribution of sulfide inclusions within the selected cross section zones of the cylindrical carbon-steel casting in solidifying in the uncooled mold in terms of the specified gas-dynamic effect.

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