IV МОДЕЛЮВАННЯ ПРОЦЕСІВ В МЕТАЛУРГІЇ ТА МАШИНОБУДУВАННІ

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Selivyorstova T. V., candidate of technical science, Mikhalyov A. I., doctor of engineering's sciences, Selivyorstov V. Yu., doctor of engineering's sciences

The National Metallurgical Academy of Ukraine, Dnipro, Ukraine

REVEALING OF REGULARITY, PROCESSING AND PREDICTION OF SULFIDE INCLUSIONS DISTRIBUTION IN CARBON STEEL THAT IS HARDENED IN A CHILL MOLD

Purpose. *To develop a mathematical model that describes the dependence of the size and amount of sulfide inclusions for various zones of the cross-section of a casting on the parameters of the gas-dynamic effect.*

Research methods. *A computer program, ASImprints, has been developed for processing digital images of sulfur imprints. Digital images of sulfur imprints of 35Л steel casting templates obtained by traditional die-casting technology and under various gas-dynamic modes were processed. A mathematical description of the nature of sulfide inclusions distribution along the casting template as a power function is proposed.*

Results. *A model of the sulfide inclusions distribution in a cross section of a cylindrical cast of carbon steel with 240 mm diameter, that solidifies in an uncooled chill mold under various gas-dynamic modes, was obtained.*

Scientific novelty. *Analytical dependences are obtained that allow interpolating parameters values of the power distribution and, thus, make a prediction of the sulfide inclusions distribution in selected areas of the cross section of this cast that solidifies in an uncooled mold under a given gas-dynamic effect mode.*

Practical value. *The suggested model makes it possible to interpolate the parameters values of a power distribution for predicting sulfide inclusions distribution in a cross section of a given cylindrical cast that solidifies in an uncooled chill mold, for a given mode of gas dynamic effect. The correlation analysis of the probability density function of the power distribution obtained for each of the considered fragments of selected casting section areas showed the statistical homogeneity of the fragments belonging to one zone and the possibility of conducting a quantitative analysis of the digital image of a sulfur imprint.*

Key words: *carbon steel, sulfide inclusions, gas-dynamic effect, analysis, distribution, ASImprints program, power dependence, forecasting.*

1 Problem statement

It is known that the solubility of sulfur in austenite and ferrite at room temperature is very low. Moreover, almost all sulfur in the steels is in the form of sulphides. Characteristics of steel depend not only on the amount of sulphides (sulfur content), but also on their size, shape and distribution. In medium-carbon cast steel with a change in sulfur concentration from 0.02 to 0.06%, the relative narrowing decreases from 53–62 to 20–47 %, and the impact toughness when testing Charpy-type samples changes from 0,8-1,1 to 0, 4–0,5 MJ / m^2 [1]. The increase of sulfur content in cast steel from 0.24 % C, 1,07 % Mn, 1.29 % Si and 0.0048 % P from 0,020 to 0.054 % according to [2, 3] reduces the impact strength more than twice. In steel 30CrNiMoL with an increase in sulfur content from 0,016 to 0.12 %, the amount of sulphides increases, their average size increases as well [1]. With an increase in the contamination of steel with sulfides, the number of microcracks arising increases, their merging is facilitated due to the decrease in the distance between inclusions. This causes a decrease in the work of crack propagation [1].

2 Review of the literature

The authors [1] established a significant dependence of plasticity and toughness on the type and nature of sulphides distribution. The eutectic sulfides, which are distributed along the boundaries of the dendritic branches, most negatively affect the mechanical characteristics, while sulfide phase of the eutectic has a branched skeleton. The total length of inclusions can vary considerably with the same amount. The most favorable form of sulfide inclusions can be considered is globular: it corresponds to the minimum contamination index and maximum values of steel characteristics [1]. In paper [2], it is noted that, from the

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point of view of density and mechanical characteristics, disoriented irregular forms of inclusions formed in steel in the presence of residual aluminum (> 0.020 %) are optimal. The size of inclusions and their distribution are significantly affected by the processes of deoxidation and modification by ferrocerium and other alloys with rare-earth elements. As a result, there is an increase in the mechanical characteristics of steel [1–3]. In addition, one of the effective methods of influencing a solidified melt is pressure, which contributes to the uniform distribution of non-metallic inclusions in the casting. Their number and size in the heat center castings made of carbon steel, for example, when punching and piston pressing are reduced by 3.5 and 1.5 times, respectively, compared to castings obtained by conventional casting methods [4]. The results of studies of the mechanical characteristics of 35L steel castings, obtained by traditional casting technology in chill mold and using gas-dynamic effects, also showed a beneficial effect of pressure on the size and sulfide inclusions distribution [5]. When implementing this technology, it is possible to influence the process of solidification by creating controlled gas pressure in the casting-gas injection system [6, 7]. Therefore, conducting research aimed at determining the patterns of sulfide inclusions distribution, their number and size in cast steel under various gas-dynamic effects, is an important task.

The aim of the paper is to carry out the processing of digital images of sulfuric imprints of 35L steel casting templates, poured into an uncooled chill mold, and based on it to obtain analytical dependencies of the size and number of sulphide inclusions for various casting section areas and gas-dynamic effect parameters.

3 Materials and methods

Casting of 35L steel (GOST 977-88) was carried out in a steel chill mold with an average wall thickness of 100 mm, a working cavity height of 550 mm and an average diameter of 240 mm. The outlet temperature from the furnace was 1640 ± 5 ° C. The gas-dynamic effect was carried out with different rates of argon pressure increase in the casting-gas supply device (Vp) system and maximum pressure indicators (P) according to the following modes:

melting N 2 – Vp = 0.04 MPa / s, P = 1 MPa;

melting N 3 – Vp = 0.08 MPa / s, P = 2 MPa;

melting N 4 – Vp = 0.12 MPa / s, P = 3 MPa.

From cylindrical castings with a height of 370 ± 5 mm and a weight of 160 ± 3 kg, obtained from traditional technology (melting N 1) and using gas-dynamic effects (melting N 2–4), templates for making sulfuric imprints were cut at 180 mm from the bottom end in the form of a disk 30 mm thick [5]. The diameter of the disc is 240 ± 3 mm.

The chemical composition of steel melting NN 1–4 is presented in table 1.

4 Experiments

The analysis of the obtained sulfuric imprints was carried out in accordance with the conditional division of the imprint area into the axial, radial and peripheral zones, based on the results of thermographic studies of solidification process of this casting [8]. The width of the axial zone along the casting radius was 40 mm, of radial zone was 60 mm, and of the peripheral one was 20 mm.

Digital images of sulfuric imprints were processed using the computer program “ASImprints”, intended for the quantitative analysis of images of sulfuric imprints [9]. The specific features of the digital images of sulfuric imprints include: color gradation of the image (shades of gray); irregular shape of areas of low brightness, corresponding to sulfide inclusions; the random nature of appearing of areas with reduced brightness; random size of areas with reduced brightness; unlimited image size [10]. In addition, in the manufacture of sulfuric imprints, often a portion of the resulting image is defective, which requires its exclusion in subsequent quantitative analysis. Therefore, it is necessary to make sure that the distribution of sulfide inclusions is uniform within the selected zones on monochrome digital images, i.e. whether a single fragment cut out of the zone can adequately characterize the quantitative parameters of the entire zone.

5 Results

During the study, 10 fragments of 10 r 10 mm in size were selected from each zone of the sulfuric imprint, and an array of values was obtained for each fragment, containing information on inclusions sizes and their number, we made graphs of the number of inclusions depending on their size. Dependence is a decreasing function that can be approximated by either power or exponential dependence. It was found that the power approximation describes more accurately the distribution of sulfide inclusions for fragments of images of sulfuric imprints of casting templates obtained both by traditional technology (Figure 1) and using gas-dynamic effects (Figure 2).

For each of the considered fragments, the probability density function of the power distribution is obtained.

Table 1 – Chemical composition of steel

N of melting	Content of chemical elements, mass. %					
	C	Mn	Si	P	S	Fe
1	0,35	0,60	0,40	0,048	0,045	rest
2	0,36	0,50	0,45	0,040	0,043	rest
3	0,38	0,55	0,41	0,045	0,040	rest
4	0,36	0,45	0,35	0,036	0,038	rest

$$N(s) = As^{\lambda} \text{ when } s \geq 0, \quad (1)$$

where A – scale factor inversely proportional to the area of the fragment, λ – power distribution form parameter.

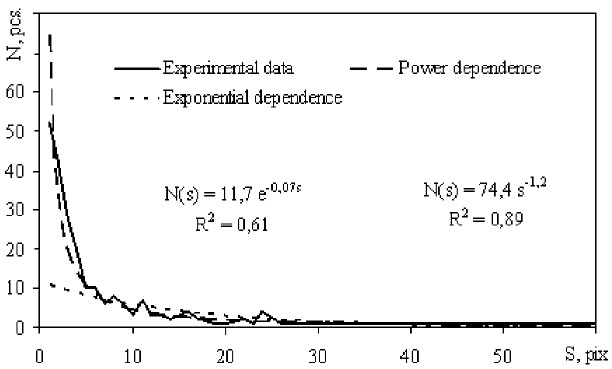

Fig. 1. The distribution of sulfide inclusions in a fragment of the image of a sulfuric imprint of the axial zone of casting template, obtained by the traditional technology

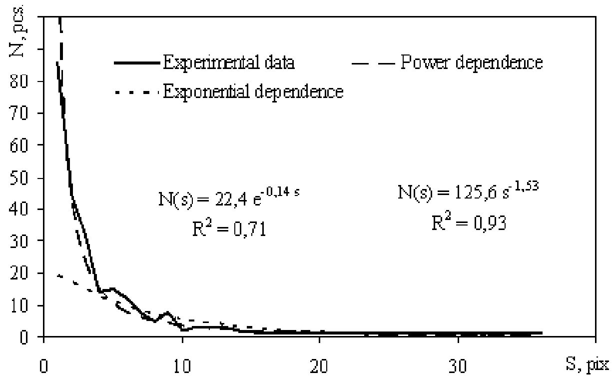

Fig. 2. Distribution of sulphide inclusions in fragment of image of sulfuric imprint of radial zone of casting template obtained using gas-dynamic effect: Vp = 0,12 MPa/s, P = 3 MPa

For values A and λ the probability density functions of the power distribution were averaged and mean-square error was calculated within the sample of images of each of the zones, characterizing the size of the possible deviation of the average values of the considered parameters from their average value (Table 2).

Table 2 – 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 A and λ for the fragments of each of the zones under consideration did not exceed 15 %, which indicates the statistical homogeneity of the fragments belonging to one zone and the possibility of conducting a quantitative analysis of the zone of the digital image of a sulfuric imprint from its fragment. In addition, the conducted correlation analysis between the arrays of the size and number of inclusions corresponding to each of the 10 image fragments and the averaged analytical dependence approximating them (Table 3) confirmed this conclusion.

To obtain analytical dependences of the parameters of gas-dynamic effect, the size and number of sulfide inclusions for different zones of casting section, one fragment was selected from each zone of the image of a sulfuric imprint. The fragment shape for each of the zones is a square with a side no larger than the width of the peripheral (narrowest) zone, which is 20 mm. The selected fragment size is 15×15 mm.

Using the computer program "ASImprints" for digital images of fragments of sulfuric imprints of cast templates obtained under different gas-dynamic modes, arrays of values of inclusions area and the corresponding number of inclusions for each of the selected zones were formed. For each of the data arrays obtained, the parameters of the probability density function of the power distribution were determined, which, as was shown above, fairly accurately describes the dependence of the number of inclusions on their size and, in particular, is confirmed by the corresponding values R^2 (Table 4).

Table 3 – The results of the correlation analysis

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

Table 4 – The parameters of the dependence functions of inclusions number and their size (probability density of the power distribution) and the accuracy of the approximation

N of melting	Casting section zones								
	Axial			Radial			Peripheral		
	A	λ	R^2	A	λ	R^2	A	λ	R^2
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

Fig. 3 and 4 show graphs of the scale factor and the shape parameter of the power distribution as a function of the gas-dynamic effect (first of all, pressure P, MPa), where dependencies resulting from the processing of image fragments correspond to solid lines with markers, and dotted lines show dependencies, approximating their linear function of the form $y(x) = ax + b$:

1 – peripheral $A(P) = 23,58\ P + 282,12$ $R^2 = 0,93$, (2)

2 – radial $A(P) = 85,54\ P + 52,13$ $R^2 = 0,93$, (3)

3 – axial zone $A(P) = 73,52\ P + 27,73$ $R^2 = 0,84$, (4)

1 – peripheral $\lambda(P) = -0,25\ P - 1,51$ $R^2 = 0,93$, (5)

2 – radial $\lambda(P) = -0,28\ P - 0,96$ $R^2 = 0,91$, (6)

3 – axial zone $\lambda(P) = -0,22\ P - 0,82$ $R^2 = 0,93$. (7)

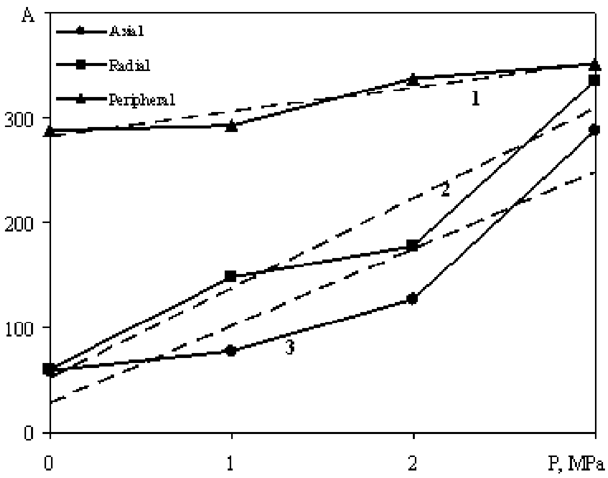

Fig. 3. A graph of scale coefficient dependence of the power distribution on pressure in the implementation of gas-dynamic effects

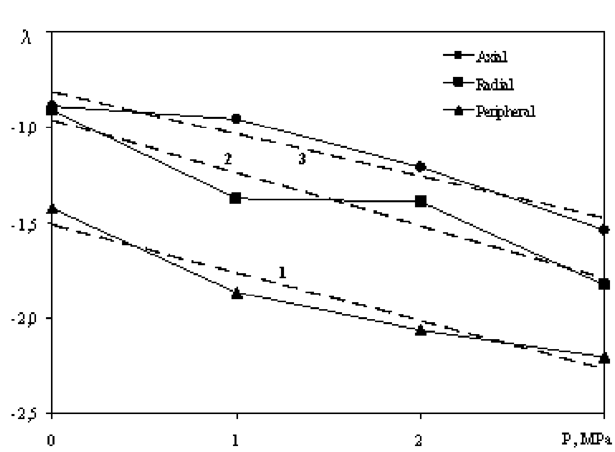

Fig. 4. A graph of shape parameter dependenceof the power distribution on pressure during the implementation of gas-dynamic effects

6 Discussion

The obtained analytical dependences (2–7) allow interpolating the values of the parameters of the power distribution and, thus, predict the distribution of sulphide inclusions in selected cross-sectional areas of this cylindrical cast, solidified in an uncooled chill mold, for a given gas-dynamic effect. Table 5 presents the comparative results of the calculation of the specific number of inclusions (Kn, pcs/mm^2) in the axial (A), radial (R) and peripheral (P) zones of the image of sulfuric imprints (8).

$$K_N = \frac{N_{IF}}{S_F}, \quad (8)$$

where N_{IF} – the number of inclusions in the fragment, pcs; S_F – fragment area, mm^2.

Conclusions

The problem of current interest of mathematical model developing that describes the dependence of the size and amount of sulfide inclusions for various cross-sectional zones of carbon steel castings poured in an uncooled chill mold on the parameters of the gas-dynamic effect has been solved.

The scientific novelty of the obtained results lies in the fact that a mathematical description has been obtained for the analytical dependences of the size and number of sulfide inclusions for various casting section areas and parameters of gas-dynamic effect. The model provides information on sulfide inclusions distribution in a cross section of a cylindrical casting poured into a chill mold without conducting full-scale experiments and additional studies of the metal structure.

The practical significance of the obtained results lies in the fact that the developed mathematical model allows us to automate the process of selecting the gas-dynamic effect modes in order to obtain cast products with a given level of properties.

Prospects for further research - to study the possibility of applying mathematical model to assess the quality of cast steel in various casting methods.

Table 5 – Specific number of inclusions, pcs / mm 2

N of melting	Specific number of inclusions, pcs / mm ^{2}								
	Experiment			Calculation			Deviation, %		
	Casting section zones								
	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

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Селівьорстова Т.В., Михальов О.І., Селівьорстов В.Ю. Виявлення закономірностей, обробка та прогнозування розподілів сульфідних включень у вуглецевої сталі, що твердіє в кокілі

Мета роботи. *Обробка серії цифрових зображень сірчаних відбитків темплетів виливків зі сталі 35Л, що заливаються в неохолоджуваний кокіль, отримання на її основі аналітичних залежностей розмірів і кількості сульфідних включень для різних зон перетину виливка і параметрів газодинамічного впливу.*

Методи дослідження. *Розроблено комп'ютерну програму «ASImprints», яка призначена для обробки цифрових зображень сірчаних відбитків. Проведено обробку цифрових зображень сірчаних відбитків темплетів виливків зі сталі 35Л, отриманих за традиційною технологією лиття в кокіль, і при різних режимах газодинамічного впливу. Запропоновано математичний опис характеру розподілу сульфідних включень уздовж темплету виливку у вигляді ступеневої функції.*

Отримані результати. *Модель розподілу сульфідних включень в поперечному перерізі циліндричної виливки діаметром 240 мм, що твердіє в неохолоджуваному кокілі при різних режимах газодинамічного впливу.*

Наукова новизна. *Отримано аналітичні залежності, що дозволяють інтерполювати значення параметрів ступеневого розподілу і тим самим скласти прогноз розподілу сульфідних включень в обраних зонах поперечного перерізу цієї циліндричної виливки, що твердіє в неохолоджуваному кокілі, при заданому режимі газодинамічного впливу.*

Практична цінність. *Запропонована модель дає змогу інтерполювати значення параметрів ступеневого розподілу для складання прогнозу розподілу сульфідних включень в поперечному перерізі даної циліндричної виливки, що твердіє в неохолоджуваному кокілі, при заданому режимі газодинамічного впливу. Проведений кореляційний аналіз функції щільності ймовірності ступеневого розподілу, отриманої для кожного з розглянутих фрагментів вибраних зон перетину виливка, показав статистичну однорідність фрагментів, що належать одній зоні, і можливість проведення кількісного аналізу зони цифрового зображення сірчаного відбитка по його фрагменту.*

Ключові слова: *вуглецева сталь, сульфідні включення, газодинамічний вплив, аналіз, розподіл, програма ASIprint, ступенева залежність, прогнозування.*

Селиверстова Т.В., Михалев А.И., Селиверстов В.Ю. Выявление закономерностей, обработка и прогнозирование распределений сульфидных включений в углеродистой стали, затвердевающей в кокиле

Цель работы. *Обработка серии цифровых изображений серных отпечатков темплетов отливок из стали 35Л, заливаемых в неохлаждаемый кокиль, получение на ее основе аналитических зависимостей размеров и количества сульфидных включений для различных зон сечения отливки и параметров газодинамического воздействия.*

Методы исследования. *Разработана компьютерная программа «ASImprints», предназначенная для обработки цифровых изображений серных отпечатков. Проведена обработка цифровых изображений серных отпечатков темплетов отливок из стали 35Л, полученных по традиционной технологии литья в кокиль и при различных режимах газодинамического воздействия. Предложено математическое описание характера распределения сульфидных включений вдоль темплета отливки в виде степенной функции.*

Полученные результаты. *Модель распределения сульфидных включений в поперечном сечении цилиндрической отливки диаметром 240 мм, затвердевающей в нехлаждаемом кокиле, при различных режимах газодинамического воздействия.*

Научна новизна. *Получены аналитические зависимости, позволяющие интерполировать значения параметров степенного распределения и, тем самым, составить прогноз распределения сульфидных включений в выбранных зонах поперечного сечения данной цилиндрической отливки, затвердевающей в нехлаждаемом кокиле, при заданном режиме газодинамического воздействия.*

Практическая ценность. *Предложенная модель позволяет интерполировать значения параметров степенного распределения для составления прогноза распределения сульфидных включений в поперечном сечении данной цилиндрической отливки, затвердевающей в нехлаждаемом кокиле, при заданном режиме газодинамического воздействия. Проведенный корреляционный анализ функции плотности вероятности степенного распределения, полученной для каждого из рассматриваемых фрагментов выбранных зон сечения отливки, показал статистическую однородность фрагментов, принадлежащих одной зоне и возможность проведения количественного анализа зоны цифрового изображения серного отпечатка по ее фрагменту.*

Ключевые слова: *углеродистая сталь, сульфидные включения, газодинамическое воздействие, анализ, распределение, программа ASImprints, степенная зависимость, прогнозирование.*