

Family of Models for Describing One Class of Metallographic Images

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Abstract—Models for images syntax are developed, tried, and tested in describing the syntax of microstructural metallographic images of wrought aluminum alloys.

DOI: 10.1134/S1054661809020187

INTRODUCTION

At the present time, there is sufficient knowledge available in the realm of digital signal processing to draw a conclusion about the structure of images [1–3]. In this case, an image is described by a multilevel hierarchic structure involving the following:

(1) The iconic level: the image is represented by the set of image elements $P = \{p_1, \dots, p_n\}$. An image element is a pixel $p_i \in P$ characterized by the family of iconic features $\{a_i\}$ including, for example, the image intensity, the gradient, the texture, and the neighbor relations on the image.

(2) The “primitive” level: the image is represented by the set of “primitive” regions $W = \{w_1, \dots, w_n\}$. A “primitive” images region $w_i \in W$ is characterized by the set of features $\{b_i\}$ including, for example, the average intensity, the gradient, the texture, the perimeter, the area, the set of features representing the form and boundaries of the region, and the neighbor relations of the region on the image.

As distinct from a pixel, a “primitive” region is represented by its own model

$$w_i = \langle P_i, \{a_i\} \rangle,$$

where P_i is a connected collection of pixels satisfying the following compactness criterion $\{a_i\}$.

(3) The “segment” level: the image is represented by a set of “segment” regions $S = \{s_1, \dots, s_n\}$ and the image background. A “segment” image region $s_i \in S$ is characterized by the set of features $\{c_i\}$ representing the form and boundaries of the region, and also the region structure and the neighbor relations of the image.

A “segment” region model is made up of a connected collection of “primitive” regions satisfying the following compactness criterion:

$$s_i = \langle W_i, \{b_i\} \rangle.$$

(4) The “segments class” level: the image is represented by a set of “segment classes” regions $K = \{k_1, \dots, k_n\}$. A class of images segments $k_i \in K$ is characterized by the set of features $\{e_i\}$ representing the properties of the class and the neighbor relations.

A “segments class” level model is made up of a connected collection of “segment” regions satisfying the following compactness criterion:

$$k_i = \langle S_i, \{c_i\} \rangle.$$

(5) The “thematic map” is made up of a set of image maps $T = \{t_1, \dots, t_n\}$. An images map $t_i \in T$ is characterized by the set of features $\{d_i\}$ representing the map properties and the neighbor relation.

A map model is made up of a connected union of “segment class” regions with the aim to analyze the following:

$$t_i = \langle K_i, \{e_i\} \rangle.$$

The first image analysis algorithms that take account of the images structure were implemented in ACRONYM, SIGMA, NAGAO, Chassery LS81, MAPSEE-3, NM80, RB84, and SPAM systems. At present, there is a substantial amount of experiments available in the developing of these systems.

The analysis system for multispectral images is aimed at the analysis of images displaying the propagation of silk moths and forest fires in the territory of the Enisei meridian. We note that the space-acquired images and metallographic images (MGI) of aluminum alloys also possess the same hierarchic syntax.

In the present article, we consider applications of the approach in question to describing the syntax with reference to the analysis of microstructural images of metallographic specimens of wrought aluminum alloys [4].

An example of a microstructural MGI of a wrought aluminum alloy relating to the “aluminum–copper” system hardenable by heat treatment is given in Fig 1a.

The image was obtained with use of an NU-2E optical microscope and a Nikon COOLPIX 950 photo-

Received December 3, 2007

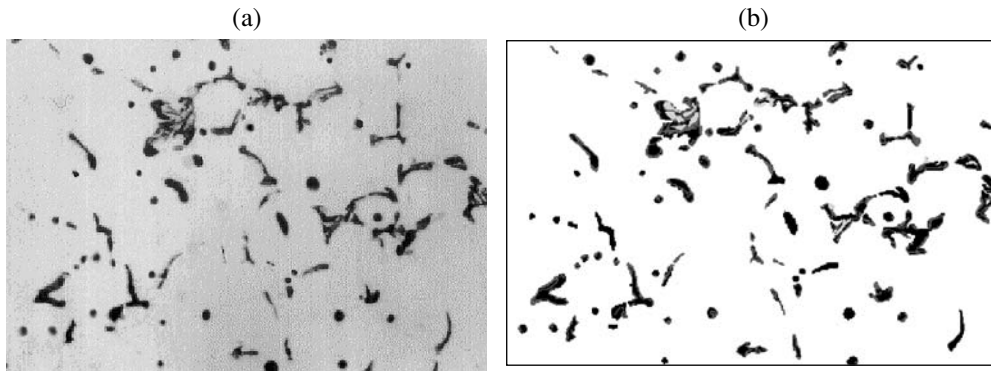


Fig. 1. (a) Microstructural image of a wrought aluminum alloy; (b) the same after the segmentation.

graphic camera from a metallographic specimen cut from an ingot core treated by mechanical polishing on a Rotopol/Rototorse grinding-and-polishing machine followed by etching with Keller’s etch with the aim at singling out the phase structure of the alloy.

In this figure are the following: an α -solid solution (relatively large light regions) and two classes of segments: lead monotectic (relatively large dark round-shaped regions) and eutectic (dark elongated regions of interlacing black and gray regions of arbitrary configuration).

1. MODELS FOR DESCRIBING METALLOGRAPHIC IMAGES

Since the images in questions are nontextured, the iconic level description involves the family of intensity and gradient (Prewitt) features.

The description of “primitive” and “segment” regions is performed with the aid of the metric features, the form features (evaluating the equiaxedness, thickness, convexity, size, intensity and “skeletshapedness” of the “segment” regions), and the functional-and-parametric features (evaluating the regions boundary properties).

Additionally, the algebra [5]

$$A = \langle \{CRM, GRM\}, \{(\rightarrow), (\cup), (\cap), (\setminus), (\vee)\} \rangle$$

was developed to describe the “segment” regions structure.

Associated with a single “segment” region there is the concretized relational model CRM_i represented as a mixed graph whose vertices correspond to the “primitive” regions and whose edges represent the inclusion and define the order relation in the vertex set. The links correspond to the adjacent relation between the vertices of one hierarchy level. The collection of “segment” regions of images defines the set of graphs, each of which can be regarded as the value of a feature with nominal scale. To describe the equivalence class of the “segment” regions, we use generalized relational mod-

els GRM_i , which are expressed in terms of a mixed graph with labeled edges.

The passage from CRM to GRM is effected by employing the operation of generalization (\rightarrow). Applying it to the relational model (RM) makes it possible to strengthen the nominal scale by changing to a scale with partial order. The order is defined by introducing an inclusion relation on the RM.

Also, we define the operations of union (\cup) and intersection (\cap), which are specializations of the well-known operations over graphs as they apply to the RMs being used. The union operation is used inferring by an RM an equivalence class of “segment” regions over RM class instances. As applied to the classification problem of “segment” regions s_i, s_j , the union operation makes it possible to use the notion of the overlap on the scale of the structural feature with the analogy of the overlap on the metric scale. However, the question of how to specify the objects that are simultaneously classified as s_i and s_j remains open. This is why we use, in addition, the operations of left (\setminus_l) and right difference (\setminus_r), which, added together, define the set of objects satisfying the properties in question.

In order to obtain a detailed classification, we use, in addition, the analysis of edge elements of “primitive” regions that make up a “segment” region [6]. In Fig. 2, we show possible variants of mutual configuration of “primitive” regions as part of a “segment” region.

The mutual configuration of edge elements of “primitive” regions that make up a “segment” is described by the following expressions:

$$b_1^2 = \langle (p_i = w_i \cap w_j) \rangle; \tag{1}$$

here is a unique edge pixel p_i of the “primitive” region w_i , and it is in adjacent relation with the edge pixel of the “primitive” region w_j .

Expression (1) corresponds to position 1a in Fig. 2:

$$b_2^2 = \langle (P_w^{**} = w_i \cap w_j) \rangle, \tag{2}$$

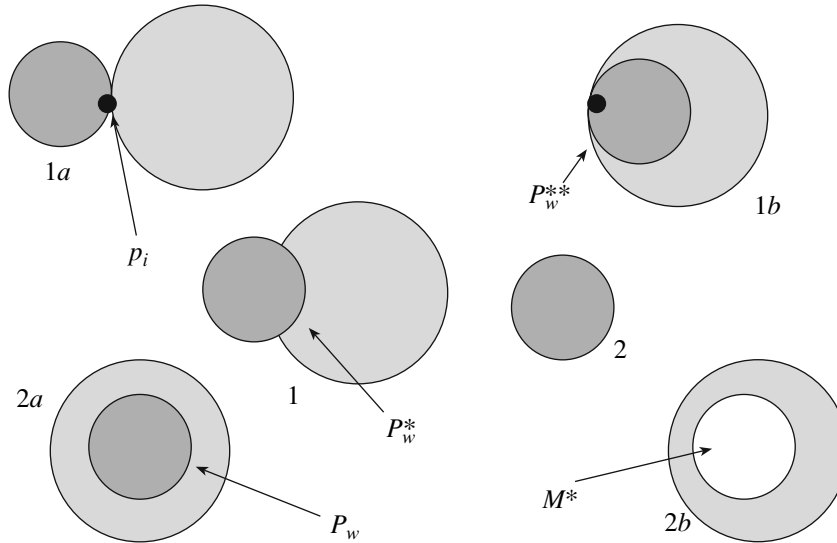


Fig. 2. Variants of mutual configuration of "primitive" regions. The background is shown in light, a "primitive" is displayed in dark.

where P_w^{***} is the subset of the set of all the edge pixels of the "primitive" region P_w such that $|P_w| - |P_w^{***}| = 1$. Expression (2) means that all the pixels except for one edge pixel of the "primitive" region w_i are in an adjacent relation with the edge pixels of the region w_j .

Expression (2) corresponds to position 1b in Fig. 2.

$$b_3^2 = \langle (P_w^* = w_i \cap w_j) \rangle, \tag{3}$$

where P_w^* is the subset of the set of all the edge pixels of the region w_i such that $|P_w^*| = [2; (|P_w^{***}| - 1)]$.

Expression (3) corresponds to position 1 in Fig. 2.

$$b_4^2 = \langle (P_w = w_i \cap M) \rangle. \tag{4}$$

Expression (4) bears witness to the fact that all the edge pixels of region w_i have an adjacent relation only with the pixels from the background M . Expression (4) corresponds to position 2 in Fig. 2.

$$b_5^2 = \langle (P_w = w_i \cap w_j) \rangle. \tag{5}$$

Expression (5) points to the fact that all the edge pixels of region w_i have an adjacent relation only with the edge pixels of region w_j ; that is, $w_j \supseteq w_i$.

Expression (5) corresponds to position 2a in Fig. 2.

$$b_6^2 = \langle (P_w = w_i \cap M^*) \rangle. \tag{6}$$

Expression (6) indicates that the edge pixels of region w_i have an adjacent relation only with the pixels from M and M^* ; that is, $M^* \supseteq w_i$.

Expression (6) corresponds to position 2b in Fig. 2.

More complex adjacent relations for "primitive" regions as part of a "segment" region are expressible in terms of the above relations.

Referring to expressions (1)–(6), a "segment" region may have the following properties:

(a) Model s_{01} ("degenerated segment") is precisely an image region consisting of one "primitive" region. In this case, the edge pixels have an adjacent relation only with the background pixels.

A "degenerated segment" region is represented by the following expression:

$$s_{01} = \langle w_i, b_i^1 \cup b_4^2 \rangle. \tag{7}$$

Relation b_i^1 of expression (7) describes the property of "primitive" regions. Usually b_i^1 is understood as meaning "to be of different intensity relative to the background" (i.e., the average intensity of the pixels composing a "primitive" region). Examples of this are the predicates "to be light gray," "to be grey," "to be black," etc.

(b) Model s_{10} ("segment") is an image region consisting of a collection of "primitive" regions W_i with $|W_i| > 1$. In this case, the "primitive" regions are in an adjacent relation with, first, other "primitive" regions constituting the "segment" region and, second, with the set of elements of the background region surrounding the "segment."

A "segment" region is represented by the expression

$$s_{10} = \langle W_i, \{b_i\}^1 \cup \{b_1 - b_3, b_5\}^2 \rangle. \tag{8}$$

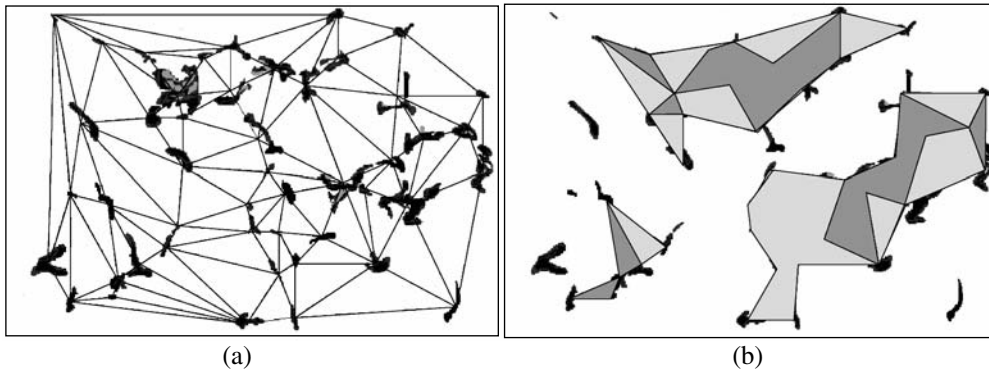


Fig. 3. Triangulation diagram (a). Regions of eutectic concentration (b).

In this case, the relations $\{b_i\}^1$ mean that a “segment” region contains “primitive” regions of various intensity.

(c) Model s_{11} (“segment with a hole”) is a region containing the background elements: the set M^* . The “primitive” regions comprising a “segment with a hole” region are in an adjacent relation with the other “primitive” regions of the set W_i , with the elements of the region M^* , and with the elements of the region M .

A “segment with a hole” region is represented by the expression

$$s_{11} = \langle W_i, M^*, \{b_i\}^1 \cup b_6^2 \rangle. \quad (9)$$

The wrought aluminum alloys are either binary or ternary. Hence, the composition of models (7)–(9) is sufficient for classifying the “segment” regions of wrought aluminum alloys.

The above algebraic system, together with the intensity, gradient, and geometric features, defines a level of detail sufficient for describing an image at the “segments” level. From the practical point of view, this furnishes a way of how to select on an image those “segment” regions that correspond to the effects on the metallographic specimen from eutectic constituents and from other phases and structural constituents. In all, the analysis results at this level are sufficient to tackle “classical” quantitative problems of metallographic analysis.

However, a number of modern studies in metal science consider problems involving the analysis of more involved phases (which, in particular, represent the concentration of the alloy component in the image area and show the regions of their mutual arrangement).

In [7, 8], together with the results of the practical analysis of metallographic images, it is remarked that some nonuniformity in the eutectic position (“segments” regions) can be looked upon as characterizing the properties of metals and alloys. In particular, the above papers highlight the influence of the concentration of eutectic and microcracks. At present, such an

analysis depends for the most part on the experience of a metallurgist.

In [9], it is proposed to calculate the value of the “segments concentration” feature $c_i(t^i)$ by using the relation

$$c_i(t^i) = NS_i / \Delta NS_i, \quad (10)$$

where t^i is the objective of the metallographic analysis (“class of segments”), ΔNS_i is the area of the triangular region formed by the three geometric centers of “segment” regions located at the minimal Euclidean distance from each other, and NS_i is the sum of the areas of the “segment” regions representing the vertices of the triangle region.

The singling out of concentration regions of “segment” regions is based on prior building of a triangulation diagram [10, 11] (Fig. 3a) of a segmented image (Fig. 1b).

Afterwards, based on the value of the “segments concentration” feature (expression (10)), one performs the singling out of the eutectic concentration regions. Regions with relatively high concentrations are drawn in Fig. 3b in dark gray. The background concentration is shown in light gray.

As the background concentration $\Delta c_i(t^i)$, we use the value of the concentration that meets the alloy’s quality requirements. For a given alloy grade, the background value is defined as the average value of a feature distribution over the whole triangular image diagram representing the ingot core.

The description of “segments concentration” regions is carried out similarly to that for “segment” regions. As a result, the “segments concentration” regions can be represented by the following models:

(1) Model k_{01} (“degenerated concentration of segments”) is a region consisting of a unique triangle of the triangular images diagram. In this case, all the “segments” of the region k_i or k_j are end segments.

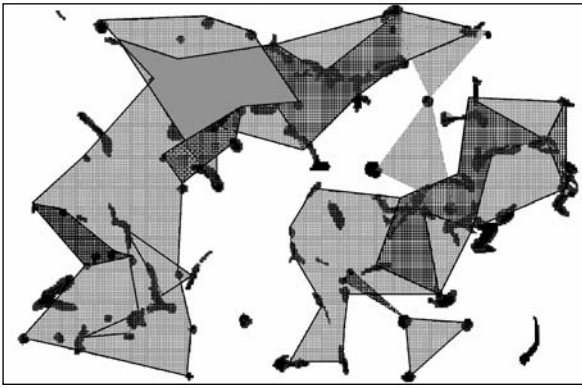


Fig. 4. Thematic map of the mutual arrangement of classes of segments.

Model k_{01} is represented by the expression

$$k_{01} = \langle v_i, \{c_i\}^1 \cup \{c_4, c_5\}^2 \rangle, \quad (11)$$

where $\{c_i\}^1$ describes the property of a region relative to the value of $\Delta c_i(t^i)$.

Examples of this are the predicates “to have a low, good, or high concentration of “segment” regions relative to the background.”

(2) Model k_{10} (“segments concentration” region) is a region consisting of triangles of the diagram with $|V^{ci}| > 1$. In this case, all the boundary “segment” regions are in an adjacent relation with boundary “segment” regions of different “segments concentration” regions and with the set of boundary “segment” regions of the background region.

Model k_{10} is represented by the expression

$$k_{10} = \langle V^{ci}, \{c_i\}^1 \cup \{c_1 - c_3\}^2 \rangle, \quad (12)$$

where V^{ci} is the set of triangles composing the “segments concentration” region.

The composition of models (11, 12) makes it possible to classify the “segments concentration” regions of microstructural metallographic images of wrought aluminum alloys.

The subsequent analysis of the mutual arrangement of “segments classes” is given as the description of the images map. The metallographic analysis involves, among many targets, the analysis of the arrangements of the phase composition and of other microstructural constituents, including microstructural defects, and also of some of their compositions.

Each elementary objective $t^i \in T$ of the metallographic analysis is some individual thematic map of the image t_i and points to the class of objects under analysis. In this case, the metallurgist’s job of specifying a target amounts to singling out essential objects of images. Some objective of the metallographic analysis may combine a family of elementary objectives, thus

forming a relatively complicated thematic map of images t_i^* .

The thematic maps of the class of images in question built on the basis of the results of investigation are divided up into two classes:

(1) A “degenerated thematic map” is represented by a unique elementary objective of the metallographic analysis and is described by the expression

$$t_i = \langle K_i, \{e_i\}^1 \cup \{e_m\}^2 \rangle, \quad (13)$$

where K_i is the collection of concentration regions of some class of essential components, $\{e_i\}^1$ are the properties of K_i , and $\{e_m\}^2$ are the properties describing the relation of a given “class of segments” with the α -solid solution.

(2) The thematic map of the image is a complicated objective; i.e., the number of classes of segments under analysis is more than one. In this case, the thematic map of an image is represented by the expression

$$t_i^* = \langle K_i, \{e_i\}^1 \cup \{e_j\}^2 \rangle, \quad (14)$$

where $\{e_j\}^2$ are the relations describing the adjacency of the essential components.

As an example, we show in Fig. 4 a thematic map of the mutual arrangement of regions of concentration of lead eutectic and monotectic.

VERIFICATION

Figure 5 illustrates the algorithm useful in the analysis of microstructural metallographic images of wrought aluminum alloys in the final checking laboratory for output goods at a metallurgical complex.

At the first stage, the algorithm performs the automated segmentation of images. If necessary, the segmentation rule may be corrected by an expert. This operation enables one to pass from the iconic level description to the description in terms of a list of “segment” regions, each of which is characterized by its own RM.

The purpose of the next stage is to perform an automatic mode evaluation of the properties of the “segment” regions on the basis of the metric and topological form features and, additionally, take into account the form of the boundary. The description result allows one to effectively identify the lead eutectic and monotectic regions. At the end of this stage, the classification of the eutectic is performed (“segment” region) in accordance with RM and with “primitive” regions adjacency models.

Next, the algorithm produces a triangulation diagram of images. Here, the substance of the matter is that the image is composed of triangular regions of minimal area. The vertices of the triangular regions are the points representing geometric centers of “segment”

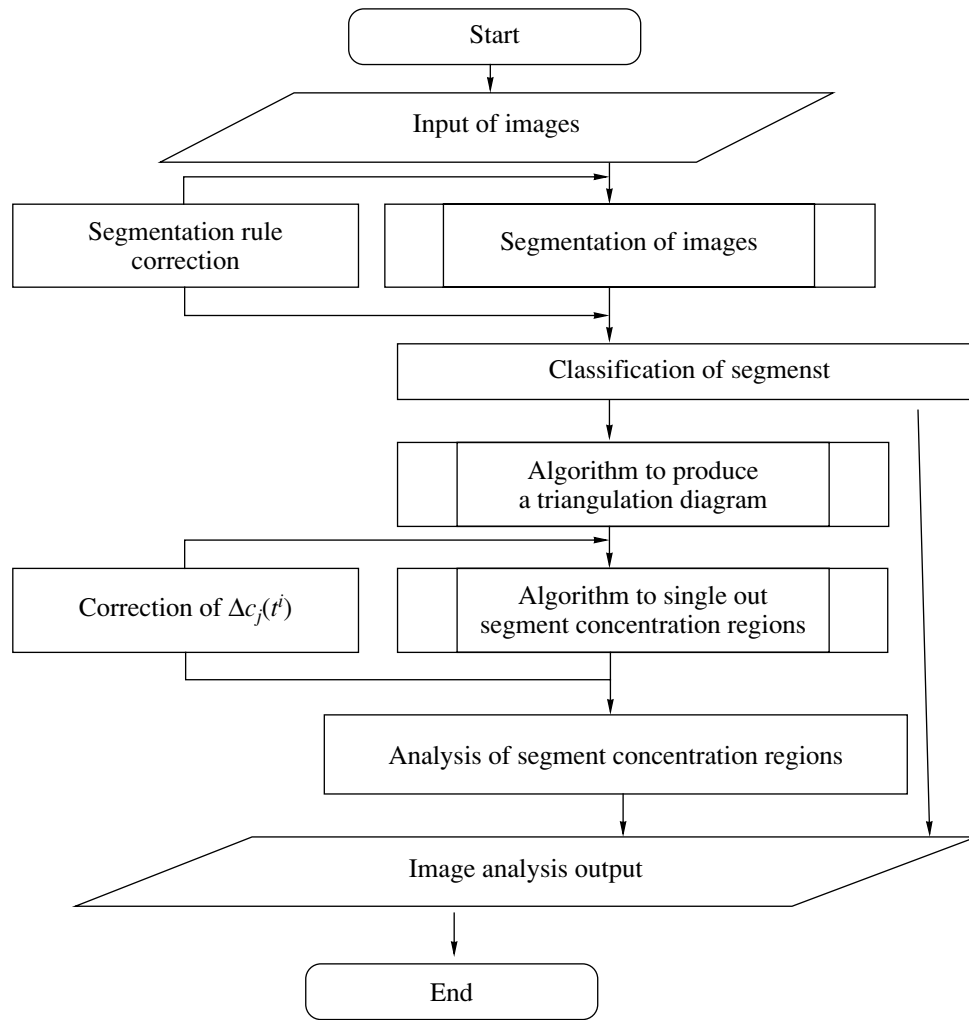


Fig. 5. Algorithm of the analysis of microstructural MGI.

regions that are located at the minimal distance from each other.

At the next step, based on the value of the “segments concentration” feature, we perform the singling out of the eutectic concentration regions. As the background concentration $\Delta c_i(t^i)$, we use the specified value for the concentration that meets the alloy’s quality requirements. The algorithm allows a user a way to correct the concentration value.

At the final stage, the algorithm performs the analysis of the concentration regions. To do this, we use an approach similar to that used for the analysis of “segment” regions.

The test experiments were conducted using a software and hardware system under the title Analysis of Microstructural Metallographic Images of Wrought Aluminum Alloys and involved the use of twenty microstructural images of an alloy ingot core. Originally, the system contained an NU-2E microscope, a Nikon COOLPIX 950 digital camera, an IBM PC (Cel-

eron 1.8 GHz, 512 Mb RAM), and original software for the analysis of microstructural metallographic images of aluminum alloys.

The main aim of the experiments was to examine the algorithm performance in the problem of singling out of “segments concentration” regions.

To do this, we first performed the segmentation of images, then identify and classify the eutectic regions, build the triangulation diagram, determine the values of the areas of the “segment” regions and of the diagram triangles, and also calculate the values of the concentration of the diagram triangles and set the background concentration value.

In the course of the metallographic analysis, the specified values and intervals of the “segments concentration” were rarely corrected by an expert. This resulted in a positive effect on the total operating time of the algorithm. However, the initial stage of the image analysis of a new alloy called for the determination of the background concentration value. In order to

increase the quality of the analysis, a metallurgist was proposed to independently correct the specified value of the alloy background concentration.

For more accuracy, we defined additional intervals representing the "segments concentration" (such as an unsatisfactory, satisfactory, and high concentration of segments). Next, a metallurgist was suggested to change the intervals values (in 90% of the tests, a metallurgist performed the narrowing of one of the intervals of his interest).

In the course of the analysis, there were located no errors involved in the algorithm failures in terms of singling out of segments concentration regions. Also, there was no erroneous allocation of the range of concentration values.

During the test experiments, it was pointed out by the metallurgists that segments with relatively large sizes and with heterogeneous composition are clustered in local parts of images and are marked as "high concentration" regions. The experiments with the correction of the intervals were aimed at the detection of the possible variance of the form and arrangement of "segments concentration" regions of images.

The current tests of the software are aimed at describing the syntax of image regions of powdered materials and of segmented images of the territory of the Enisei meridian.

CONCLUSIONS

The family of models developed has been tried and tested in describing of metallographic images of wrought aluminum alloys. The iconic level involves a combination of intensity and gradient features. The describing of the syntax of "segment" regions uses a combination of the featured and structured approaches. At the "segment level" we use, as a means for describing, the algebra defined on the set of RM "segment" regions with a signature that involves the following operations: generalization, union, intersection, and the left and right differences. The analysis of the ways of adjacency of "primitive" regions is taken as providing additional information enabling the classification of "segment" regions. An original feature that enables one to single out the "segments concentration" of microstructural MGI of wrought aluminum alloys is presented. Based on the analysis of the relations of the boundary "segment" regions, we developed models of the "segments concentration" that enable us to classify the concentration regions for essential components of microstructural MGI of wrought aluminum alloys. A new description of the thematic map of the microstructural MGI of wrought aluminum alloys was developed allowing one to analyze the mutual arrangement of "segments concentration" regions of images.

ACKNOWLEDGMENTS

This work was supported by the Russian Ministry of Education and Science under grant no. 2.1.2.5594 in the framework of the program "Development of the Higher School Scientific Potential."

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