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THE ASSESSMENT OF GAS TURBINE VANES BASED ON THE WATERSHED SEGMENTATION OF THEIR SURFACE IMAGES

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Abstract

The article discusses the linkage between the colour changes of the recorded surface images of vanes and their state. For this purpose, we used a selection of techniques and methods for processing and analysis of digital images (pre-processing, watershed segmentation,) for the colour representation other than RGB model [2, 4]. Difficult to interpret pixel information was replaced with an area information (extracted in the process of segmentation areas with certain characteristics and attributes – the relationship between the state of the vane and its colour). The proposed colour representation of the surface of the vanes (HSV model) allows separation of image data – the separation of luminance (brightness) from the colour (chrominance). This enables better interpretation of the obtained results of segmentation, and thus the quality of the resulting diagnostic information is increased. The obtained results allow the introduction of the tri-status classification of the vanes (operable, partially operable, and inoperable). The study adopted operated vanes (with different technical state) of gas-turbine stator vanes of an aircraft jet engine, made from ŻS – 6K alloy. The digital surface images (photos) of vanes were recorded after their dismantlement, by the use of a digital camera (fixed conditions of registration, selection of the appropriate light source, uniform illumination of the photographed surfaces, no reflections). This information is essential for the on-going, non-destructive assessment of the technical state of vanes.

Keywords: *turbine vanes, colour surface, watershed segmentation*

1. Introduction

In the process of the operation of gas turbines occur damages to their components. These damages are of different form and intensity. Some forms of damage are detectable in operation by means of a visual method using a videoscope [10]. Furthermore, the analysis of the literature [9, 10, 15] shows that only a small number of defects of turbine components results from defects in materials, design and technology. Instead, a common cause of damage is overheating of the material, and thermal fatigue of the vanes (especially uncooled ones) of the nozzle apparatus and the rotor caused by both excessive heat and its duration, as well as the chemical activity of the exhaust [1, 2, 5, 6, 12]. The process of destruction of gas turbine blades/vanes begins with coating (shown on the surface images in the form of a colour change). As a result, the blade/vane material is exposed to direct, aggressive exhaust impact. This situation causes overheating of the blade/vane material, revealing adverse changes in its microstructure. During the whole operation process occur changes in colour of the blades/vanes surface. These colour changes are the result of varying degrees of the material overheating [1, 3, 4, 7]. Fig. 1a shows the non-overheated vane (usable) and the overheated vane (Fig. 1b), impossible for further use.

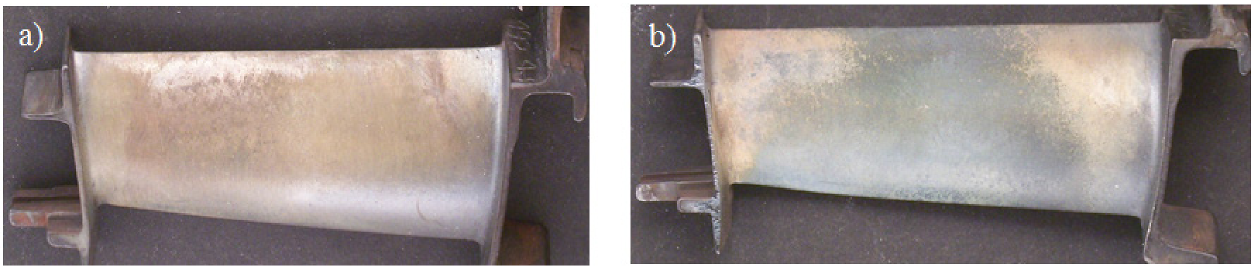

Fig. 1. Stator vanes of the gas turbine (ŻS – 6K alloy) with different degrees of overheating

Overheating of the vanes/blades is the result of exceeding acceptable average value of exhaust gas temperature as well as non-uniform temperature distribution at the periphery of the gas turbine. Currently, the decision about the need to repair the engine is taken by a diagnostician who, using a visual method with a videoscope, can diagnose the state of the turbine components that are difficult to access. Evaluation of the state is made on the basis of the recorded image of the surface of the element to be diagnosed and by comparison of this image with standard surface images of usable and unusable, analogous turbine vane components. Tab. 1 shows exemplary colours of the oxide layer and the corresponding temperature at the fracture of the vane in case of cooling in air.

Tab. 1. Temperature at the fracture of the vane and the corresponding colour – conditions of cooling in air [3]

Temperature [K]	Colour of the oxide layer at the fracture of vane
670	light grey
770	light grey with faint yellow
870	light yellow
920	yellow, dark yellow
970	yellowish brown
1020	yellowish brown with a shade of purple
1070	dark purple
1120	blue, navy

Such criteria for evaluation of the state are very subjective, because they depend on the knowledge and the eyesight of a diagnostician. The decision of diagnostician is verified by the destructive method. The tested element is subjected to analysis of the microstructure on metallographic specimen. Mistakes in subjective evaluation of the diagnostician can lead to the recognition of overheated vanes as usable and non-overheated vanes as unusable. Consequently, in the first case, there is a plane crash in a short time the engine is running; in the second case, there are huge costs of the repair of the main engine.

2. Research object and data recording

The study adopted operated of a gas-turbine stator vanes of an aircraft jet. The vanes were manufactured of the ŻS-6K alloy. An important technological issue in this type of alloys is thermal treatment, which mainly consists in homogenizing annealing (unification of the structure, increase in strength and plasticity) [3, 14]. The purpose of treatment is also to obtain a fine dispersion and shape of phase γ' precipitates, as the main strengthening phase. Then a protective coating is applied, which allows increasing the operating temperature, additionally protecting the base material against the harmful effects of the working medium (exhaust gas) of high temperature (Tab. 2).

Tab. 2. Heat treatment of vanes made of ŻS-6K alloy [3]

Homogenizing annealing	Aluminium-silicon coating application
In a vacuum, 1225°C, 4 hours, cooled under argon to 900°C for 10 min;	1. Applying a layer of AS2/350 ml collodion cotton solution, 112g Al powder, 112g Si powder 2. Diffusive annealing, 1000°C, 3 hours, slow cooling.

In the initial state, the aluminium-silicon surfacial layer is uniform over the entire circumference of the vane. This layer consists of two sublayers – the outside one with a higher content of Al and the intermediate with a higher content of Si, which is also richer in carbide forming elements (especially Mo, W). After long periods of operation occurs degradation of the aluminium-silicon layer, linked to the reduction in the thickness of the outer layer. It has a higher Al content, and the intermediate layer has a higher Si content as in the initial state. In the intermediate layer, there are pores and the carbide precipitations, Mo, W, increase.

In the article the analysis of vane's colour (the evaluation of state) was made on the basis of images of vanes (JPEG format with a low compression ratio, preserving all the necessary information and details) dismantled from the turbine. For this type of registration of image data, it is possible to ensure high reproducibility of the data, obtained by setting fixed terms of acquisition (selection of an appropriate light source, uniform illumination of the photographed surfaces, no glare etc.).

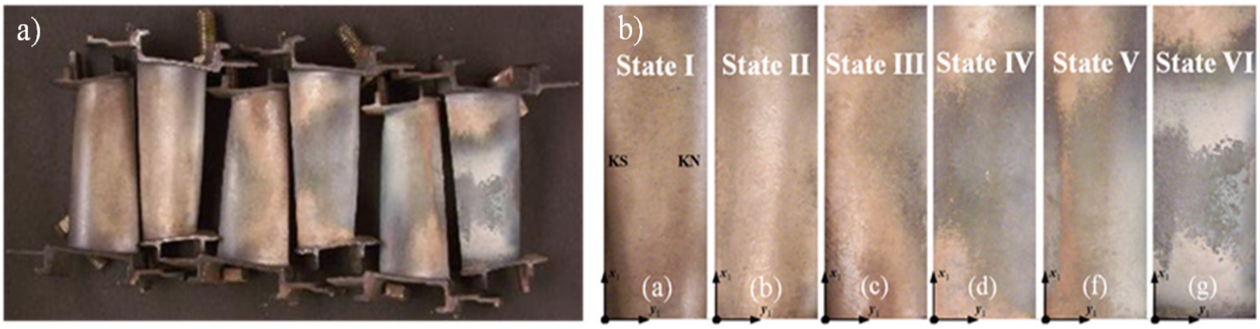

Fig. 2. Nozzle guide vanes of gas turbine: a) image of the surface recorded using a digital camera; b) separate surfaces with the accepted classification according to the state of overheating (a-f)

Figure 2b shows an exemplary set of vanes with the previously used classification of their technical condition (the degree of overheating) with the adopted coordinate system (where x, y – dimension of the vane's picture in pixels, z – the saturation of RGB colour). In contrast, images taken using the videoscope (working conditions), due to the minimization of image capture device and point sources of light, are affected by geometric distortion and colour misrepresentation. Moreover, the sensor device is unstable and movable, thus characterized by the lack of repeatability of exposure and uneven lighting of tested elements [8].

3. Colour representation of the images of vanes surfaces

Due to high correlation between individual channels of the *RGB* colour space (low quality of the obtained information), before the segmentation, a conversion to *HSV* space was made [16]. With such treatment, it was possible to separate chrominance (channel *H* and *S*) from luminance (channel *V*). Hannel H (Hue) determines the frequency of the light wave and expressed in units of angle from 0 to 360 degrees, assigned to portion of visible light by Newton. *H* takes on a shade of orange to yellow, green, blue, purple to red. *S* (Saturation) determines the colour saturation from white to monochrome and *V* (Value) defines the level of white light. The applied mathematical description is presented below. The conversion from *RGB* to *HSV* model:

$$R' = \frac{R}{255},\ G' = \frac{G}{255},\ B' = \frac{B}{255}, \tag{1}$$

$$C_{max} = max\left(R',G',B'\right),\ C_{\min} = \min\left(R',G',B'\right), \tag{2}$$

$$\Delta = C_{max} - C_{min}, \tag{3}$$

Hue calculation:

$$H = \begin{cases} 0^{\circ}, & \Delta = 0, \\ \left(\dfrac{G'-R'}{\Delta} \bmod 6\right)\cdot 60^{\circ}, & \mathrm{C}_{\max} = R', \\ \left(\dfrac{B'-R'}{\Delta} + 2\right)\cdot 60^{\circ}, & \mathrm{C}_{\max} = G', \\ \left(\dfrac{R'-G'}{\Delta} + 4\right)\cdot 60^{\circ}, & \mathrm{C}_{\max} = B'. \end{cases} \tag{4}$$

Saturation calculation:

$$S = \begin{cases} 0, & C_{\max} = 0, \\ \dfrac{\Delta}{C_{\max}}, & C_{\max} \neq 0. \end{cases} \tag{5}$$

Value calculation:

$$V = C_{max}. \tag{6}$$

4. Watershed segmentation

The idea of watershed segmentation is based on the topological concept of watershed. The brightness assigned to each pixel of the image is interpreted as a rise above a certain level reference [11, 13]. Under this assumption, the image shows the topographical surface and the drops falling on it run off in the direction of the steepest inclination, into the recesses of the land (minima of the image). All points of land from which water flows to the same minimum are its runoff basin, and each such basin corresponds to a segment of the surface image. Boundary lines separating individual pools from each other are called watershed lines [11, 13]. It is important that the digital image subjected to watershed segmentation be previously appropriately transformed, so that the edges of objects in the image were maxima of image, while the surfaces of objects – minima. The transformation that meets the given assumptions is a gradient of image, which can be obtained by using gradient operators or as a result of the relevant morphological operations.

Six vanes of different status of surface overheating (Fig. 2a) were converted to the image data contained in Tab. 3. Additionally, Tab. 3 sets down the range of data that was read out from the histograms of these images (range of variation). The exception is the *H* channel of *HSV* model for which only the number of the adopted shades was given.

The channel of *H* shade, *HSV* model, transmits information about the colour of the pixel. Images of this channel (Fig. 3a) are characterized by a multi-modal distribution of the histograms (from 0 to 255, i.e. in the entire range of possible data). The greater the range of channel *S* values (Fig. 3b), the greater the differences in pixel values. Tab. 3 shows that the distribution of histogram's data range is very wide. This allows the assumption that the given channel will best describe the colour changes on the particular surfaces of the vanes being in a different technical condition.

Tab. 3. The ranges of data accepted on each channel of vanes images

		State I	State II	State III	State IV	State V	State VI
H	number of levels	70	47	55	104	147	209
S	range	7-255	25-157	19-190	3-116	0-119	0-132
	number of levels	254	132	171	113	119	132
V	range	23-255	95-255	61-251	112-255	104-222	70-244
	number of levels	232	160	190	143	118	174

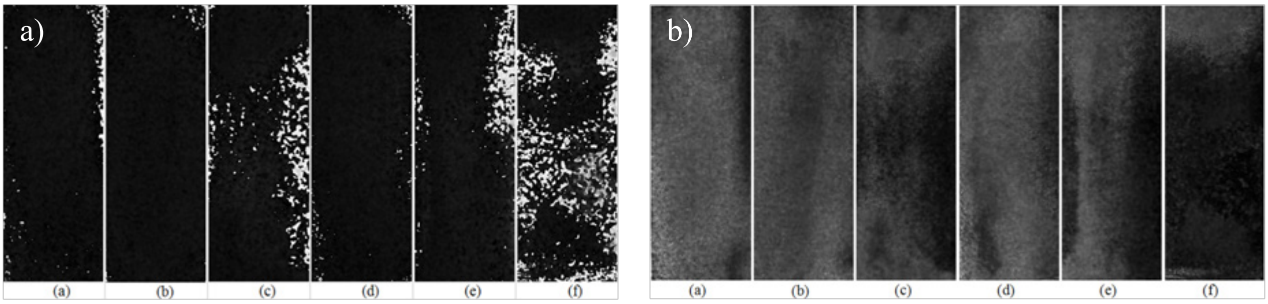

Fig. 3. Surfaces of vanes (a-f) in HSV: a) H channel; b) S channel

5. Description of the algorithm

The block diagram of the steps implementing watershed segmentation of images of the surface of vanes (the next steps of image processing and analysis) has been included in Fig. 4.

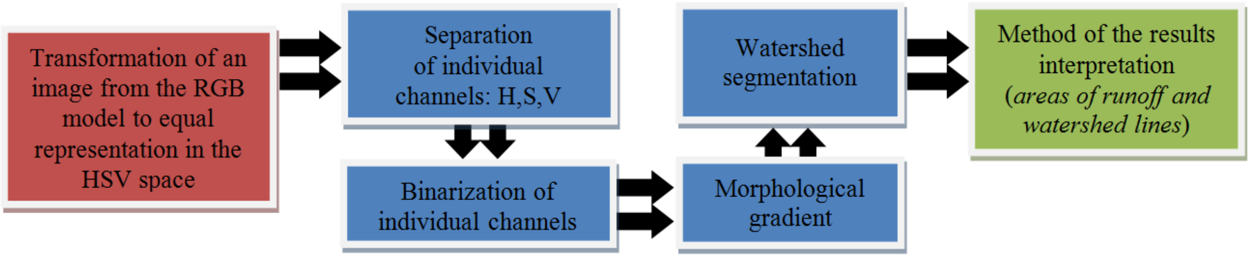

Fig. 4. A block diagram of the procedure used to carry out the image segmentation

To watershed segmentation is subjected the gradient image which takes non-zero values at the edges of objects. Minimums of the image represent the surfaces of objects. The image that meets the given assumption is a morphological gradient of a digital image. It is determined by the difference of image after dilatation operation and image after erosion operation. The use of morphological gradient of intensity image, that is, for example, one of the channels of any colour space, is not an appropriate approach. The gradient of such image is also an intensity image, which results in excessive segmentation. Individual channels of earlier assigned models were subjected to binarization. Then, the binarized images of channels underwent the operations of dilatation and erosion. As a result, morphological gradients were determined for each channel of *HSV* model. The next step was watershed segmentation, the result of which was the obtainment of images with watershed lines and runoff areas.

The interpretation of runoff areas and watershed lines only is not possible, therefore pseudo-colouring was considered, dependent on the average pixel value of the runoff areas. This involved the determination of the average value of each runoff area of a given series of vanes (a series of vanes is understood as images of all vanes of the same model channel). Then to watershed, lines and runoff areas have been assigned the new values responsible for the colour of areas. The determination of these values has been made according to the following formula:

$$I_n = 0.9 \cdot \frac{I_s - I_{min}}{I_{max} - I_{min}}, \tag{7}$$

where:

I_n-<0. 9> – colour value assigned to a given runoff area,
I_s – the average value of the runoff area,
I_{min} – the lowest average value selected from all areas of a series of images,
I_{max} – the highest average value selected from all areas of a series of images.

The spectrum of colour varies in the range of 0 to 0.9, because in the process of assigning colours *HSV* model is used, which has 0 to 1 scale of colour tone changes. The red colour is in the ranges of 0-0.05 and 0.9-1. Therefore, in order to avoid ambiguity of colour, the scale was limited to 0.9 value. Originally, pseudo-colouring consisted of rescaling the range of 0-255 to 0-1 but such an approach, with narrow histograms, has not confirmed well. The reason for this was low colour resolution of the basin area, and thereby worse distinguishing of colour assigned to them.

In Fig. 5a, b are shown the results of pseudo-colouring of the runoff areas resulting from watershed segmentation.

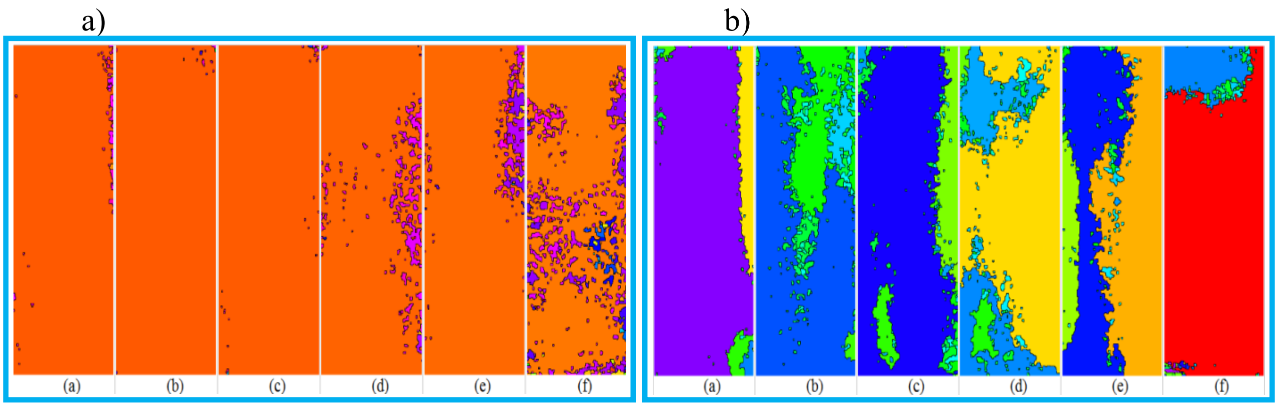

Fig. 5. Exemplary result of the watershed segmentation of the surface images of vanes being in a different technical condition (a÷f) – HSV model: a) H channel; b) S channel

From the visual evaluation of received images, we can draw the following conclusions. In the image of *H* channel (Fig. 5a) we cannot distinguish basins that could be recognized as areas of the overheating of vanes' surfaces (only some "suspicious" areas can be seen on vanes d, e, f). In the images of *S* channel (Fig. 5b) a large variety of basins' colours was obtained. The comparison of their position on the surfaces with the original photographs (Fig. 2b) supports the conclusion that red, orange and yellow colours define the place of overheating the vanes material. The images of chromaticity of *HSV* model accurately reflect the perceptions of a diagnostician. Examination of the images and graphs corresponding to the channels of chromaticity allows specifying the degradation process of the surfaces of vanes. On the basis of observation and the used scale of changes in pseudo-colouring, the areas covered with certain colours can be divided as follows:

– the standard surface (operable element) – marked by colours: blue, purple, pink,
– surface slightly damaged (partly operable element) – marked by colours: light blue, green,
– surface heavily damaged (inoperable element) – marked by colours: red, orange, yellow.

Figure 6 presents the graphs of percentages, showing an area covered with particular colours, corresponding to the images from Fig. 5b (*S* channel, *HSV* model).

The area of vane marked with the (f) letter is degraded to the greatest extent. As much as 87% of the total surface of the vane is suspected of overheating.

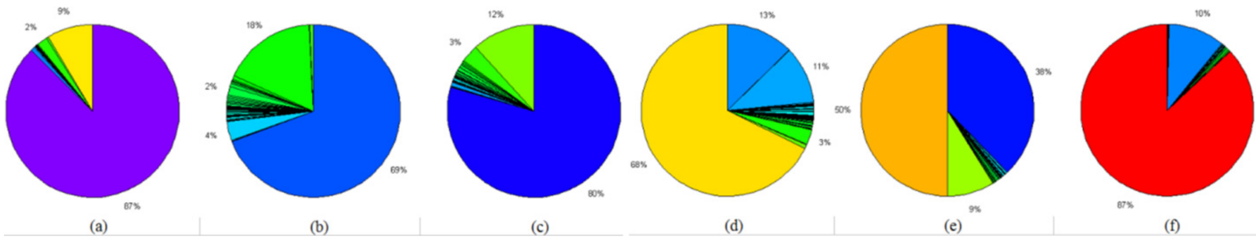

Fig. 6. Percentage of specific colours on the tested surfaces according to the runoff areas – S channel

Summary

The analysis conducted in the article demonstrated that for the detection of overheated areas of the coating of turbine vanes it is best to use the S chromaticity channel of *HSV* model (Fig. 5b, 6). On the other hand, the V channel, carrying information about brightness (luminance), introduces ambiguity in the case of improper lighting of the vane's surface. The resulting images of segmentation and the graph of percentage occurrence of the specific colours on the analysed surfaces (Fig. 5b, 6) enable the observation of changes taking place on the surface of the vane. It is also possible to determine three states of the suitability of the tested elements. Further exploitation of the vanes belonging to the last of them (the unusable element) is associated with a high risk of damage. Areas of the overheated surface of these vanes covered over 85% of the total.

The proposed, computer-aided method has many advantages. One of them is the omission of the decisive, human factor. For the visual studies very important is the experience of the operator, as the results are encumbered by the subjective assessment of a diagnostician.

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