Complex approach for monitoring the parameters of the wire

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Abstract. The paper briefly describes the diffraction method for measuring the diameter of long-length products such as metal wire, optical fiber, chemical fiber, metal ingots or nonmetal. A method and optical device for monitoring the diameter and surface temperature of such products are proposed. The main advantage of the proposed method is to monitoring the parameters of the heated product even on the defocused image. In this paper we propose a set of methods that can improve the accuracy of measuring the diameter and temperature of such products. The methods are based on optical phenomena and digital image processing methods.

1. Introduction
For modern methods of manufacturing thin extended products, such as wire, it is necessary to use optical devices that allow monitoring the diameter and temperature of such a product at the time of its pulling out of the melt of the common billet [1-6].

The paper proposes a comprehensive approach to obtain smaller errors in the measurements. The method is based on the optical diffraction phenomenon and allows measurements of both parameters even on the defocused image in real time [7].

2. Materials and methods of research

2.1. Diffraction method for measuring the diameter of thin objects
Fig. 1 shows the scheme of obtaining the image of the shadow of the wire (a), the scheme of determining the diameter of the wire using the known diffraction method (b) [8, 9].

As a point source of radiation a design of a powerful led and an adjustable slit was used. The narrow slit allows to obtain a large resolution of the diffraction pattern [10].

When using an optical system (OS), it is necessary that the condition \( r_i > y_{\text{min}} \), where \( y_{\text{min}} \) is the minimum resolution of the optical system, to be met.
2.2. Measuring the diameter of thin objects from an defocused image

Fig. 2 shows the scheme of changing the scale of the shadow of the wire image when moving the product at a distance from the focus point of the OS rays along the optical axis.

The smaller the diameter of the object, the harder for OS to build its exact copy on the defocused image. Theoretically, this is determined by a Gaussian beam. It follows that the formula that allows to measure the diameter of the object is expressed as

$$D_{\text{wire}} = l_{\text{px}} \frac{X_R - X_L}{(M_{\text{OS}}M_{\text{shadow}}) - 2b \tan \beta}$$

where $l_{\text{px}}$ – the physical size of the matrix pixel; $M_{\text{OS}}$ – linear magnification of the OS; $M_{\text{shadow}}$ – the scale of the product shadow image; $\beta$ – the angle that shows how the beam is distributed when the distance between the object and the focal plane changes.
Figure 2. Changing the scale of the product image shadow as it moves along the optical axis: $f_1$ - front focusing length; $\beta_{D_{\text{max}}}$ and $\beta_{D_{\text{min}}}$ - angles that indicate the deviation of the diameter measurement result on the defocused image from the actual diameter of the product, for the maximum and minimum diameters respectively.

The angle $\beta$ can be defined in two ways:

- with the difference of distances $b\{t\}$ and $b\{t_0 + t_1\}$ in a short period of time $t_1$, provided that the product can move in three coordinates (with vibration of the product);

- by pre-calibrating the device using reference objects with minimum and maximum diameters (full or partial calibration).

The use of two methods at the same time can increase the probability of determining the angle $\beta$.

2.3. Image processing of diffraction pattern

2.3.1. Method of measuring the diameter of the product. The accuracy of the measured diameter depends on how close the results of the measured $\Delta_x$, $b$, $\beta$ to the actual values, so the most important problem is the accuracy of the measurement of the coordinates of the boundaries and centers of diffraction extrema.

Preliminarily, it is necessary to obtain a background image, the brightness distribution of which will be compared with the brightness distribution of the wire image.

Fig. 3 is a scheme of determining the coordinates of the boundaries and centers of diffraction extrema using the proposed method. Previously, a similar method was used to measure the diameter of the heated wire on the focused image [11]. The segment $\Delta_x$, which is based on the similarity of two right-angled triangles, is determined by

$$\Delta_x = \left(1(x,y) - 1_0(x,y)\right) \sin \gamma / \cos \gamma,$$

where $l(x,y)$ is the image coordinate $(x,y)$, $\gamma$ is the angle between the hypotenuse and the leg.

The brightness distribution of individual diffraction maxima and minima of the resulting diffraction pattern can be distorted by the noise of individual matrix pixels and airy disks, which are formed by defects of OS components. Such airy disks do not change their position in the image, and the noise is not constant and chaotic, so the possibility of using the proposed method depends on the sensitivity of the radiation receiver.

To reduce noise, a spatial smoothing filter with dimensions $N \times N$ can be used, but even with such filtering, there is a possibility that the maximum brightness, which corresponds to the coordinate of the radius of the first maximum $r_1$, may not be determined correctly. Therefore, using the comparison of the measured radii of diffraction extrema with the actual values, which are determined by the Fresnel zone plate formula makes sense.
The algorithm for determining the coordinates of the object shadow boundary:

- to obtain the center coordinates of the diffraction extrema;
- to determine the radii of Fresnel rings (preliminary, without the first radius);
- the first radius $r_1$ can be determined as shown in Fig. 1, (b), namely
  \[ r_1 = \Delta r \frac{r_1}{(r_5-r_1)} = 1.366 \Delta r; \]  
  \[ (3) \]
- to determine the distances $a$ and $b$ (the implementation of the method is described in [7])
  \[ b = M_{shadow} \frac{r_1^2}{\lambda}; \]  
  \[ (4) \]

where $\lambda$ is the wavelength;

- to make a comparison of the measured radii with the real ones, which are calculated on the basis of the known formula of the Fresnel zone plates:
  \[ r_m = \sqrt{m \lambda ab/(a+b)}, \]  
  \[ (5) \]

where $m$ – number of the Fresnel zone;

- the closest to the actual result can be used to determine the radius of the first ring $r_1$ – a segment that allows to determine the boundary of the shadow of the object;

- the distances $a$ and $b$, which were used to calculate the diffraction pattern according to the formula (5), can be used to obtain more accurate results and additional parameters – scale $M_{shadow}$, angle $\beta$, etc.

2.3.2. Temperature measurement method. Temperature measurement and monitoring using optical methods is based on the results of measuring the brightness of the surface area of the radiating heated object [4, 7, 11].

When displacing a heated object from the focal plane of the OS device, there is a certain distance at which the brightness at the central point of the image of this object practically does not change its value (or the error will be insignificant). This is shown in Fig. 4.

To improve the accuracy of measurements, it is necessary to process the vicinity of the central point on the image of the heated wire using an averaging filter. Dimensions $N$ can be expressed as

\[ N = y_{min} M_{OS}/l_{px}. \]  
\[ (6) \]

The result of the averaging filter will be the average brightness value $\overline{I}(T)$, which is measured in brightness gradations (br.gr.) and is determined, as is known from [12], by the formula
\[ I(x', y', T) = \frac{1}{N_{x,y}} \sum_{(x,y) \in S_{x,y}} I(x,y), \]  

(7)

where \( S_{x,y} \) is the area with the center at the point \((x,y)\), \( I(x,y) \) is the original image.

![Fig. 4](image_url). The dependence of the displacement of the heated wire with 497 \( \mu \text{m} \) diameter at a distance from the focal plane of the optical system: where "0" – focused image; "+" – defocused image of the object when it approaches the point source of radiation at a certain distance (in \( \mu \text{m} \)); "-" – defocused image of the object when it approaches the optical system at a certain distance.

The most important issue is the ratio of the background image brightness to the image brightness of the heated wire \( I_0/I(T) \). Thus, when we have \( I(T) \geq 0.5 I_0 \), the total brightness (brightness of the shadow and the brightness of the heated surface of the object) makes it impossible to determine the diameter of the wire due to a violation of the geometry of the diffraction pattern.

Therefore, when measuring the temperature in a wide range of values without reducing the resolution of the OS, the solution may be to change the brightness of the point source of radiation and the frame rate of the matrix when forming the image.

3. Results and discussion

The results of the calculation of the errors of the proposed methods are given in tables 2 and 3. The errors were expressed by the standard deviation. The results are given for the test object – wire with diameter \( 202 \mu \text{m} \) of NiCr alloy.

### Table 1. The comparison of the error results of the methods used to measure the diameter

| Method                | Error \( \Delta_{\text{diam}}, \mu \text{m} \) |
|-----------------------|---------------------------------------------|
| Standard              | \( \pm 18 \)                                    |
| Advanced standard     | \( \pm 12 \)                                    |
| Diffraction           | \( \pm 6 \)                                     |
| Advanced diffraction  | \( \pm 4 \)                                     |

### Table 2. The comparison of the error results that are used to measure the temperature at the center point (advanced diffraction method)

| Method     | Error \( \Delta_{\text{temp}}, \) br. gr. | Error \( \Delta_{\text{temp}}, ^\circ \text{C} \) |
|------------|------------------------------------------|-----------------------------------------------|
| 1x1 mask   | \( \pm 1.69 \)                           | \( \pm 6.25 \)                               |
| 3x3 mask   | \( \pm 1.19 \)                           | \( \pm 4.4 \)                               |
| 5x5 mask   | \( \pm 0.94 \)                           | \( \pm 3.46 \)                               |
| 7x7 mask   | \( \pm 0.93 \)                           | \( \pm 3.45 \)                               |

The standard method of measuring the diameter of the product involves obtaining a diameter by counting the number of pixels whose brightness is equal to
In this case, instead of a point source of radiation (slit), an illumination system is used, the design of which consists of the led and an OS.

The standard advanced method was described earlier in [11]. The design of the lighting system is similar to the standard method.

The diffraction method expresses the diameter of the product by determining the boundaries of the object shadow.

The diffraction advanced method expresses the receipt of the diameter of the product using the material from paragraph 2.3.

4. Summary

The paper proposes a comprehensive approach to improve the optical method of monitoring simultaneously two parameters of the heated wire in real time during its manufacture at high temperatures, involving the use of image processing methods such as spatial filtration (averaging filter).

The algorithms have been developed and applied to determine:

- the contours of the diffraction maxima and minima on the formed diffraction pattern;
- an angle that shows how the beam is distributed when the distance between the wire and the focal plane changes.

The complex approach proposed in this paper allows to increase the accuracy of the measurement of the diameter and temperature of the heated wire in the process of its manufacturing.

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