Method and device for testing the parameters of the wire from NiTi alloy in the high-temperature manufacturing process with use an inert gas

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Abstract. NiTi alloy is a shape memory alloy that can be applied in various fields of science and technology. The use of NiTi alloy wires in the design of the engine reduces energy consumption to drive the engine mechanisms and improve economic efficiency in general. In this paper, we propose a method and improved design of an optical device to check the diameter and temperature of the surface of the NiTi wire at high temperature during its manufacture in an inert atmosphere. Brief information about high-temperature manufacturing processes of extended cylindrical products is given. The monitoring algorithm for both parameters of the wire was proposed and the main errors was deduced. The required temperature range for the NiTi alloy at a wire die-less drawing is determined.

1. Introduction

The products made of alloys with shape memory effect are used in most fields of science and technology (medicine, engineering, aerospace technology, etc.) [1-4].

NiTi (nitinol) alloy is one of the most popular among them because of its specific properties. However, due to various factors, the manufacturing process and processing of NiTi products are quite complex: it is necessary to adhere to strict requirements for the alloy homogeneity, temperature distribution, geometric parameters of the product [5]. In the production of NiTi alloy products, the scrap rate can reach 50%.

In some cases, traditional methods of manufacturing and processing of alloy products with shape memory effect do not allow to monitor all the required parameters. Therefore, instead of traditional drawing methods, high-temperature methods can be used [6-10].

2. Materials and Methods

2.1. Methods of High-manufacturing Process

For a general introduction to the high-temperature processes for the manufacture of extended cylindrical products, such as pipes, wires, etc. Figure 1 shows schemes of two such processes [6-10]. Figure 1,a shows a scheme of a die-less drawing method. Figure 2,b shows one of the possible schemes for improving the process of manufacturing wire of different diameters, where it is necessary to observe a certain feed rate of two materials, which are fed simultaneously to one slot of the threaded rod, as well as a melting temperature regime.
The main parameters of manufacturing (processing) of wire of NiTi alloy with the die-less drawing reproduced from work [11]:

- The temperature range (maximum temperature) of the wire surface, \( T_{\text{max}} \sim 700-900^\circ\text{C} \).
- The range of wire diameters \( D_{\text{wire}} \) can be different (the paper provides information for the rod with an average diameter of 5 mm).

**Figure 1.** Scheme of high-temperature manufacturing process of an extended cylindrical object with use inert gas: (a) die-less drawing; (b) high-temperature manufacturing; \( V_1 \) – feed rate; \( V_2 \) – drawing speed; 1 – object; 2 – induction coil; 3 – cooling system; 4 – inert atmosphere; 5 – illuminator; 6 – wire from Ni; 7 – wire from Ti; 8 – block; 9 – heating element; 10 – motor; 11 – screw system; 12 – nozzle (die); 13 – block.

2.2. *Testing Method of the Wire Parameters*

The majority of scientific works, which describe the process of die-less drawing of products, use optical devices to monitor their diameter and surface temperature [6-8].

Earlier, we proposed an optical device for monitoring the diameter and temperature of the surfaces of extended cylindrical products. The developed device is based on the use of the known method for determining the diameter of the diffraction pattern [12], as well as the method of measuring the temperature by setting the brightness threshold and changing the scanning frequency [13, 14].

The figure 2 shows the scheme for determining the diameter and temperature of the wire surface. Detailed information on the definition of the constant \( k \) is contained in work [12]. The principle of operation of device with using these methods can be found in [12, 14].

**Figure 2.** Scheme for measuring the diameter and temperature distribution of the surface of the wire: a) scheme obtain diffraction pattern; (b) diffraction pattern; 1 – light source; 2 – wire; 3 – optical system; 4 – light filter; 5 – radiation receiver; \( a \) – distance between light source and wire; \( b \) –
distance between wire and focal point; \( f_1, f_2 \) – focus distance; \( \Delta_r \) – length between 1st and 3rd zones Fresnel; \( k \) – constant value; \( M_{\text{shadow}} \) – scale of a shadow; \( M_{\text{OS}} \) – scale of an OS; \( I(T) \) – bright, which depends on temperature; \( X_L, X_R \) – coordinates of the shadow borders.

However, when using an inert atmosphere, the obtained measurement results may contain additional errors that can be caused by the uneven spectral composition of the radiation (linear spectrum), as well as by the purity of the gas. Thus, it is advisable to improve the design of this device in order to increase the reliability of the measurement results.

2.3. Device Design

Figure 3 shows a scheme of the device design for monitoring the parameters of the wire in the process of die-less drawing in an inert gas environment (vacuum chamber is not shown).

![Figure 3](image_url)

**Figure 3.** Optical device for testing the parameters of wire in die-less drawing process: (a) scheme of the device; (b) scheme of the stand; (c) photo of the stand and device; (d) wire image (camera 1); (e) spectrum image (camera 2); 1, 2 – matrix of photosensitive elements (CMOS-matrix); 3 – servo; 4 – narrow-band light filters; 5 – diffraction grating; 6 – servo; 7 – lens; 8 – beam splitter; 9 – diaphragm; 10 – lens; 11 – diaphragm (slot); 12 – light source (LED); 13 – object (wire); 14 – induction coil; 15, 16 – coupler; 17 – lead screw; 18 – lead screw nut, 19 – device, 20 – stand.
The result of the study of the radiation spectrum, which was formed by the heated product in an inert gas environment, allows to adjust the results of the measured parameters of the wire. In the scheme of the device there is an element that allows you to distribute the radiation intensity along the wavelengths – a diffraction grating (or prism), as well as a unit with several interference filters, which are used depending on the composition of the gas (mixture) and its purity.

2.4. Algorithm for Testing the Parameters of the Wire

The monitoring algorithm of wire parameters in accordance with the proposed integrated approach:

- To determine the coordinates of the product location in the image.
- To measure the brightness of the background and the surface of the heated product, as well as to determine the ratio of these brightness.
- To compare the result with the required (threshold value), and change the scanning frequency and brightness of the light source (backlight) to the required.
- To determine the distance between the product and the focal plane of the optical system.
- To measure the brightness of the heated product at the selected wavelength using the main matrix.
- To analyze the spectral composition of the radiation – to assess the uniformity of the distribution of the radiation brightness along the wavelengths in the image and to determine the brightness at the desired wavelength (or in a narrow range).
- To measure the diameter of the product (at several wavelengths), as well as to make a correction of the result.
- To measure the temperature of the product (at several wavelengths), as well as to make a correction of the result.

2.5. Deviations

The deviation $\delta_{diam}$ can be represented by several components:

- $\delta_{Lc}$ – determination deviation $\Delta_{Lc}$ (distance between two centers of diffraction maxima). In determining the coordinates $X_L$, the deviation $\delta_{Lc}$ can be expressed as

$$\delta_{Lc} = \left( \frac{X_L - X_{Lc}}{k} \right) \cdot \Delta_{Lc},$$

where $X_{Lc}$ is the coordinate of the first extremum that corresponds to the radius $r_{Lc}$;

- $\delta_{r}$ – definition deviation $\Delta_{r}$ (similar to (3));

- $\delta_{M_{shadow}}$ and $\delta_{M_{OS}}$ are deviations of the scope determinations $M_{shadow}$ and $M_{OS}$, respectively. Such errors depend on the calculation of the overall design of the optical device (focal lengths, the distance between the light source and the optical system, etc.).

The device deviation $\delta_{dist}$, which occurs when measuring the distance $b$ between the object and the focal plane of the optical system, can be represented by several components:

- $\delta_{b}$ – deviation in determining the actual distance $b_{real}$. Expressed as

$$\delta_{b} = \frac{M_{shadow} \cdot \lambda_{b_{real}}^2}{\lambda_{b_{real}}},$$

where $\Delta_{r}$ is the deviation in determining the actual distance $b_{real}$. Expressed as

$$\delta_{b} = \frac{M_{shadow} \cdot \lambda_{b_{real}}^2}{\lambda_{b_{real}}} = \frac{M_{shadow} \left( 1.366 \left( \Delta_{r} \pm \delta_{r} \right) \right)^2}{\lambda_{b_{real}}},$$

(4)
where $\delta_{rr}$ is the deviation of determination $\Delta_{rr}$ (distance between two centers of diffraction extrema);
- $\delta_{bb}$ – deviation in determining the actual distance $\delta_{\text{real}_b}$ (the expression is similar to the expression (4));
- $\delta_{bs}$ – deviation in determining the distance $b$ from the array of values that were calculated on the basis of the set threshold value $s_b$ in the software implementation of the method [14]. It follows that $\delta_{bs} \leq s_b$.

3. Result and Discussion

The figures 4-6 show the results of temperature calibration of the device for two metal wires of Ni and Ti – the dependency diagrams of the wire surface temperature against the radiation detector exposure are shown.

Calibration was performed using industrial thermometer MASTECH MS6514 and K-type thermocouple.

On the presented diagrams you can see a certain pattern: the two curves intersect at a point that corresponds to a temperature $T$ of approximately 790-810°C. Suggesting that in the process of manufacturing products from NiTi alloy it is necessary to adhere to this temperature range.

The results of processing the experimental data, which are shown in figures 4-6, were obtained on the basis of work with the prototype of the described device.

![Figure 4](image_url)  
**Figure 4.** Results of the calibration device for the temperature of the surface of the wire at a brightness of 40 b.g.

![Figure 5](image_url)  
**Figure 5.** Results of the calibration device for the temperature of the surface of the wire at a brightness of 50 b.g.

![Figure 6](image_url)  
**Figure 6.** Results of the calibration device for the temperature of the surface of the wire at a brightness of 60 b.g.
Low-cost CMOS-matrix devices do not allow to register low light conditions at the required scanning frequency. However, the use of modern high-tech CMOS-matrix or CCD-matrix with the required characteristics will significantly improve the efficiency of the method.

4. Conclusion
The paper proposes a method and an improved design of the optical device for monitoring the parameters of the wire of NiTi alloy with the shape memory effect at high temperature during its manufacture in an inert atmosphere.

Brief information about high-temperature manufacturing processes of extended cylindrical products is given. Brief information on the measurement of the diameter of extended cylindrical objects using the diffraction method is given. The monitoring algorithm for both parameters of the wire was proposed and the main errors was deduced.

Based on the results of the calibration of the device by the temperature of the surfaces of two wires, which are made of Ni and Ti metals, it can be concluded that the required temperature range in the manufacture of products of NiTi alloy. Experimentally, the temperature range was set at 790-810 °C.

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