Laser marking of contrast images for optical read-out systems

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Abstract. In the present study the formation of contrast images that provide functionality of optical read-out systems is considered. The image contrast is determined by the difference of reflection coefficients of the beryllium surface covered with titanium nitride film (TiN) formed by physical vapor deposition and the image created on it by laser oxidation. Two ways of contrast variation are studied: by regulating both TiN reflection coefficient during vapor deposition and the reflection coefficient of the image obtained with the laser. The test results show the efficiency of the proposed approach.

1. Introduction
Traditional techniques for marking metal surfaces include electrochemical, chemical, etching, and mechanical processes that are typically used for functional image formation. All these ‘standard’ marking techniques damage the surface or strongly change its surface properties. However, in some application areas, contrast image is required to be created with minimum changes of surface properties. A clear example is a rotor of an electrostatic gyroscope that contains a contrast image on its surface, providing functionality of an optoelectronic read-out system of the gyroscope [1]. Surface homogeneity determines dynamic characteristics of a spherical rotor during its high speed rotation. The quality of the pattern defines the accuracy of data acquisition from a spinning rotor. For this reason, the technical process of pattern formation is of great importance [2]. The work described in this paper is focused on the development of a process for contrast image formation on titanium nitride surface without surface roughness and shape deviation. This task is proposed to be solved using a localised laser oxidation process. A pulsed fiber laser was used to treat a titanium nitride film deposited on beryllium substrates in the air with intensities below an ablation threshold to provide oxide formation.

2. The object and purpose of investigation
The objects of the research were spherical beryllium samples with a diameter of 10 mm and surface roughness $R_a=0.05 \mu m$, with a 1 µm titanium nitride coating using physical vapor deposition (PVD) before laser treatment.

The main purpose of the work was to create a pattern consisting of 8 stripes on TiN surface with the required contrast ratio $K=0.5\pm0.1$ measured on a read-out system with a wave length of 860 nm without deviation of pattern roughness from the basic surface roughness.

3. Theoretical issues
One of the most important characteristics of the pattern is its optical contrast $K$, which is defined by the difference between the reflection coefficients of the basic surface $R_{TiN}$ and those of the pattern
surface $R_r$ formed by the local laser modification of the basic surface, described by the following formula:

$$K = \frac{R_{TiN}(\lambda) - R_r(\lambda)}{R_{TiN}(\lambda) + R_r(\lambda)}$$

(1)

$R_{TiN}$ and $R_r$ — reflection coefficients of titanium nitride and pattern surfaces, respectively, $\lambda$ — the wavelength of the optoelectronic read-out system equal to 860 nm. It is possible to plot lines of equal contrast (figure 1) for various combinations of $R_{TiN}$ and $R_r$, using formula (1).

![Figure 1. Lines of equal contrast.](image)

Lines 1 and 2 from figure 1 show the possibility of getting the desired contrast of 0.5-0.6 for different combinations of $R_{TiN}$ and $R_r$. Obviously, the contrast value $K$ can be regulated by changing reflection coefficients $R_{TiN}$ during vapor deposition of titanium nitride thin film and $R_r$ during laser treatment. The laser oxidation technique was chosen because of its high performance and versatility in comparison with anodizing or photolithography [3, 8].

It is required to provide the contrast value $K$ with the minimum level of the thickness of the pattern layer formed by a localised laser oxidation process. This condition can be met if the contrast value $K$ is achieved with a minimum level of $R_r$. According to figure 1, for line 1, the minimum value of $R_r$ is equal to 0.038 and the corresponding level of $R_{TiN}$ is 0.15. Such calculations determine how to achieve the maximum contrast with the minimum impact of a laser treatment.

Regulation of $R_{TiN}$ is possible by forming TiN-coating with non-stoichiometric composition described by formula Ti$N_x$, where $x$ is taken from the range of values from 0.58 to 1, corresponding to the coating color from light to dark golden. It is important to note that hardness of non-stoichiometric composition of titanium nitride films is much higher than that of stoichiometric one [4]. This phenomenon is very useful in our research because it is possible to create a strong thin film on the rotor surface that protects beryllium surface from damage in the case of the emergency shutdown.

The exact composition of titanium nitride coating is regulated by the partial pressure of nitrogen gas used during the vapor deposition process. For example, the nitrogen pressure of 0.013 Pa provides a coating having the light golden colour, the range of gas pressure from 0.1 to 0.8 Pa forms a coating having the golden colour and it’s possible to get the dark golden colour using the pressure of 1.04 Pa.

Minimisation of $R_r$ is correlated with decreasing laser power that defines the roughness and the depth of the modified layer. The reflection coefficient of the pattern $R_r$ is regulated by laser modes. During the research the laser power was determined as the most significant parameter of laser treatment. Considering laser marking as a thermally activated process, described by the Arrhenius
equation [5], assuming that $R_r$ decreases exponentially under decreasing laser power, using nonparametric approximation, it is possible to obtain the following equation:

$$K \approx K_{\text{max}} - Ae^{-P_0/P_0}$$

(2)

$K_{\text{max}}$ is the maximum available value of the contrast, $P_0$ is the power corresponding to the level when $R_r$ decreases by a factor of $e$, $A$ is a constant that depends on the material properties. The approximation of equation (2) by the experimental data is shown in figure 2.

![Figure 2. Experimental and approximation curves for $K=f(P)$.](image)

The curves presented in figure 2 show that the experimental results are in a good agreement with the results of calculations, for more detail, see [6]. For laser marking of titanium nitride with non-stoichiometric composition described by formula $TiN_{0.9}$, such approximation allows one to determine the values of $K_{\text{max}}$, $P_0$ and constant $A$, as follows $K_{\text{max}} = 0.93$, $P_0 = 0.148W$ and $A = 1.1 \cdot 10^4$.

4. Experimental details

A thin film of titanium nitride coating was formed by cathodic arc deposition (PVD method). Nitrogen pressure was selected in the range from 0.1 to 0.2 Pa to create golden colour. The choice of medium pressure is explained by the additional requirements for $TiN$ coating to provide a high level of wear resistance and hardness with minimum defects. The dependence of $TiN$ coating hardness from the level of nitrogen pressure was considered in [7]. It was shown that the maximum of hardness with minimum defects corresponds to the range of nitrogen pressure from 0.081 to 0.104 Pa.

$TiN$ coating formed by cathodic arc deposition with partial pressure of nitrogen equal to 0.16 Pa has surface reflection coefficient $R_{TiN}$ equal to 0.15. The dependence of nitrogen pressure on the reflection coefficient was determined empirically.

The following pattern was created in the air using a commercially available machine based on an ytterbium pulse fiber laser with $\lambda = 1.06 \mu m$ wavelength. In the process, the pulse width $\tau$ was 4 ns, the average power $P_{\text{aver}}$ and the pulse repetition frequency $f$ were 5 W and 99 kHz, correspondingly. The laser spot with a focal diameter of $d_0 = 50 \mu m$ moved over the sample surface with a velocity of 85 mm/s. This mode provides an optical contrast without changes of surface roughness $R_a=0.05 \mu m$ and was obtained experimentally, based on the theoretical issues mentioned before.

Four colours (golden, brown, purple and blue) were obtained using the described mode by changing numbers of passes. Golden colour was obtained after the first pass, brown - after the second laser scanning of exactly the same place, purple - after the third pass, and blue - after the forth pass. Multipass laser treatment was used as the method to increase contrast gradually with the minimum thermal exposure at the maximum resolution. The following values of the contrast, calculated according to formula (1), were obtained from optical analysis of the treated areas: 0.14 for golden
colour area, 0.39 – for brown, 0.53 – for purple, and 0.6 – for blue colour. The laser mode forming the blue colour pattern with contrast 0.6 was used in the further study.

The surface roughness of the treated layers was measured using the roughness measuring station Hommel Tester T8000. The surface roughness of the samples was evaluated by calculation of the standard roughness parameters presented in table 1.

**Table 1.** The roughness parameters before and after laser oxidation of TiN coating.

| Roughness parameters, µm | $R_a$ | $R_q$ | $R_z$ | $R_{max}$ |
|--------------------------|-------|-------|-------|-----------|
| Before laser oxidation   | 0.05  | 0.08  | 0.38  | 0.52      |
| After laser oxidation    | 0.05  | 0.08  | 0.39  | 0.58      |

The experimental data from table 1 shows that the set of roughness parameters remains unchanged after laser treatment, which indicates that the formation of a color image is carried out by the laser local oxidation without initialization of evaporation process. Contrast image formation was realised by localised laser oxidation with generation of color thin films. Approximate thickness of color films is about 100 – 400 nm. The titanium oxide film described by formula $TiO_2$ and oxynitride with composition $TiO_{0.34}N_{0.74}$ were detected by XDR analysis after multiple laser treatment of the titanium nitride thin film.

5. Experimental results

The pattern consisting of 8 stripes (4 wide and 4 narrow) was marked by laser on the spherical sample covered with TiN coating. The optimal modes for vapor deposition and laser oxidation were obtained experimentally, based on the theoretical issues mentioned before. Then the sample included in read-out system was subjected to test, using the emitting-receiving optical sensor. Results are shown in figure 3.

![Figure 3(a,b).](image)

**Figure 3(a,b).** (a) View of the pattern obtained from the optical read-out system; (b) signal from the optical sensor in the equatorial zone of the spherical sample.

From figure 3(a) one can see that the read-out system scans eight stripes formed by a laser. These stripes have clear boundaries and the high level of the homogeneity. Figure 3(b) shows that the optical sensor detects 4 wide and 4 narrow stripes rather clearly. Detailed description of functionality of the optoelectronic read-out system with a pattern created by laser oxidation process can be found in [8].

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*Surface and Coating Technology* **191** 317–23

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