X-ray contrast study of a medical nickel-free shape memory alloy TiNbTaZr

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Abstract. The study of the X-ray contrast of a nickel-free shape memory alloy TiNbTaZr for medical purposes of various compositions was carried out by theoretical calculation of the linear attenuation coefficient and the evaluation of the linear attenuation coefficient by the flaw detection method due to obtaining a contrast image. From the data obtained, it can be argued that all the obtained Ti-Nb-Ta-Zr materials have a radiopacity, the more the higher the content of niobium and tantalum.

1. Introduction

Materials with shape memory and concomitant superelasticity have broad application prospects, incl. in medicine. But most of the well-studied alloys in this category contain toxic elements, corrosive destruction in the body, etc. [1-7]. Relatively recently, it was discovered that the manifestation of the memory effect and superelasticity is also possible for beta-titanium alloys with a niobium and tantalum content of 20-40% and zirconium up to 8 at. %, i.e. only non-toxic metals [8-14].

For the implanted material to be radiopaque, which is necessary for tracking the position and condition of the device during installation and operation, it must have a radiographic density higher than that of the surrounding host tissue and have sufficient thickness to influence the transmission of X-rays to create contrast in the image [15].

One way to quantify this absorption characteristic is the atomic attenuation coefficient, which is directly proportional to the linear attenuation coefficient and the atomic number of the absorbent element. The linear attenuation coefficient characterizes the absorption capacity of the substance. Biocompatible elements with a range of atomic numbers from 22 to 83 and having linear attenuation coefficients in the range from 5.46 to 151.53 cm-1 at 50 keV should provide sufficient radiopacity. Preferred metal elements for biocompatibility and radiopacity are titanium, zirconium, tantalum, and platinum.
This work was aimed at studying the radiopacity of a nickel-free shape memory alloy TiNbTaZr for medical purposes.

2. Materials and methods
A theoretical calculation of the linear attenuation coefficient and an assessment of the linear attenuation coefficient by the flaw detection method was carried out due to the obtaining of a contrast image in accordance with GOST 20426-82.

The equipment for the study consists of an X-ray apparatus that transmits samples lying on the panels and flat matrix detectors (panels), the action of which is based on the conversion of the incident X-ray radiation directly into a digital image of the object (Figure 1). Distance between top and bottom 800 mm.

When the X-ray emitter is turned on for a given exposure time, the radiation flux passing through the control object falls onto the detector, which causes the scintillator to glow, which is directly connected to the photodiode array. The glow is read by the detector. The small pixel dimensions allow the imaging unit to achieve a high-resolution shadow image that is digitally recorded in the control unit. The control unit performs digital processing and image filtering. Then the image of the controlled object is displayed on the screen of the control unit.

The samples were placed on the panel according to Figure 2. The top row consists of reference wire samples and a product weaved from our wire. The bottom row contains wire samples of various compositions (Table 1).

| Sample number | Composition          | Wire thickness, mm |
|---------------|----------------------|--------------------|
| 1             | Ti-20Nb-10Ta-5Zr     | 0.28               |
| 2             | Ti-25Nb-10Ta-5Zr     | 0.28               |
| 3             | Ti-30Nb-10Ta-5Zr     | 0.29               |
| 4             | Ti-20Nb-13Ta-5Zr     | 0.28               |
| 5             | Ti-25Nb-13Ta-5Zr     | 0.28               |
| 6             | Ti-30Nb-13Ta-5Zr     | 0.27               |

3. Results and discussion
The linear attenuation coefficient for complex substances should be determined by the formula 1:
where \( \mu_1, \mu_2, \ldots, \mu_n \) are the linear attenuation coefficients of radiation of an 1, 2, ..., n element that is part of a complex substance;
\( \rho_1, \rho_2, \ldots, \rho_n \) - density of an 1, 2, ..., n element that is part of a complex substance;
\( \eta_1, \eta_2, \ldots, \eta_n \) - the relative mass fraction of an 1, 2, ..., n element that is part of a complex substance;
\( p \) - is the density of a complex substance.

The results of calculating the linear attenuation coefficient for Ti-Nb-Ta-Zr materials are shown in Table 2.

| Material       | Density | Linear attenuation coefficient |
|----------------|---------|--------------------------------|
| Ti-20Nb-10Ta-5Zr | 6.91    | 20.23 |
| Ti-25Nb-10Ta-5Zr | 7       | 22.32 |
| Ti-30Nb-10Ta-5Zr | 7.11    | 24.52 |
| Ti-20Nb-13Ta-5Zr | 7.15    | 21.89 |
| Ti-25Nb-13Ta-5Zr | 7.28    | 24.19 |
| Ti-30Nb-13Ta-5Zr | 7.29    | 26.12 |
| Ti             | 4.51    | 5.40  |
| Nb             | 8.58    | 55.00 |
| Ta             | 16.68   | 94.95 |
| Zr             | 6.53    | 38.90 |

From the data obtained, it can be argued that all Ti-Nb-Ta-Zr materials obtained have a radiopacity, the more the higher the content of niobium and tantalum.

The attenuation coefficient is a dimensionless physical quantity that characterizes the degree of decrease in the radiation power after it travels a certain distance in a medium or as a result of reflection from the interface between two media. Evaluation of the linear attenuation is carried out by obtaining a contrast image.

After shooting, a high-resolution shadow image is obtained (Figure 3). By changing the contrast and brightness of the image, it becomes possible to compare the intensity of the outgoing beam, which makes it possible to assess the reflectivity of the material and, by comparing with reference samples, to estimate the linear attenuation coefficient.
To assess the linear coefficient of attenuation of the material, it is necessary to conduct a comparative analysis with reference samples, the data for which are given in Table 3.

**Table 3. Parameters of reference samples**

| №  | Linear attenuation coefficient, cm\(^{-1}\) | Material | Diameter, mm |
|----|------------------------------------------|----------|--------------|
|    |                                          |          | d1  | d2  | d3  | d4  | d5  | d6  | d7  |
| 1  | 15.15                                    | Iron     | 0.40 | 0.32 | 0.25 | 0.20 | 0.16 | 0.125| 0.10 |
| 2  | 22.758                                   | Copper   | 0.20 | 0.16 | 0.125| 0.10 | 0.08 | 0.063| 0.05 |
| 3  | 22.758                                   | Copper   | 1.25 | 1.00 | 0.80 | 0.63 | 0.50 | 0.40 | 0.32 |
| 4  | 0.972                                    | Aluminum | 0.101| 0.124| 0.157| 0.252| 0.324| 0.404|-     |

Focusing on the Ti-Nb-Ta-Zr alloy wire (Figure 4), it can be established that the closest contrast was an iron wire standard with a thickness of 0.4 mm and a linear attenuation coefficient of 15.15 cm\(^{-1}\), and a wire standard of copper with a thickness of 0.40 mm and 0.32 mm and a linear attenuation coefficient of 22.758 cm\(^{-1}\).

Based on the fact that the wires of the Ti-Nb-Ta-Zr alloy have a diameter of 0.27 to 0.29 mm, which is less than the diameter of wire standards made of copper and iron with similar contrast, it can be concluded that the linear attenuation coefficient of the Ti-Nb-Ta-Zr is similar to copper at about 22.758 cm\(^{-1}\).

**Figure 4.** High-resolution shadow image with focus on a Ti-Nb-Ta-Zr wire sample (a - iron d = 0.4 mm, b - copper d1 = 0.40 mm, d2 = 0.32 mm)

4. Conclusions
The study of the X-ray contrast of a nickel-free shape memory alloy TiNbTaZr for medical purposes of various compositions was carried out by theoretical calculation of the linear attenuation coefficient and the evaluation of the linear attenuation coefficient by the flaw detection method due to obtaining a contrast image.
From the data obtained, it can be argued that all the obtained Ti-Nb-Ta-Zr materials have a radiopacity, the more the higher the content of niobium and tantalum.

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