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Digital image correlation of coated and uncoated Religa Heart_Ext ventricular assist device

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The digital image correlation is used to estimate influence of deposited heamocompatible coatings (gold and titanium nitride) on mechanical response of ventricular assist device Religa Heart_Ext made of Bionate II (thermoplastic polycarbonate urethane) under working conditions by comparison of the coated Religa Heart_Ext with uncoated Religa Heart_Ext. The DIC is applied for experimental investigation of the strains and displacements distribution on external surface of the blood chamber of ventricular assist device during loading. The experiment was conducted in a hydraulic system with water at operating temperatures of 25 and 37 °C, as well as under static pressures: 80, 120, 180, 220 and 280 mmHg, and static underpressures: –25, –45, –75 mmHg. The subsequent images were taken after stabilization of pressure on a set level. The applied research method shows that the nano-coating of 30 nm in thickness significantly affects deformation of the blood chamber of Religa Heart_Ext in macro scale. The proposed composition of coatings increases strain on external surface of the ventricular assist device.

Key words: *ventricular assist device (VAD), digital image correlation (DIC), titanium nitride (TiN), gold (Au)*

1. Introduction

The developed ventricular assist device (VAD) Religa Heart_Ext [2] is made of Bionate II (thermoplastic polycarbonate urethane) and it is presented in Fig. 1. In order to increase athrombogenic features the Religa Heart_Ext is planned to be coated by haemocompatible titanium nitride (TiN) by the PLD (pulsed laser deposition) method. The material of coating has a much lower ductility than polyurethane, thus the micro-mechanical tests (micro-tensile test [6], [8] and micro-shear test [7]) were performed for specimens made of the VAD wall materials. The micro-mechanical tests and their models showed how surface of the VADs should be coated [7] due to strain and stress states, as well as cracks' occurrence. They proved which composition of deposited materials is the most optimal [8] and which set of deposition parameters leads to the best quality of coatings [12]. Because the significant residual stress is observed in TiN coatings deposited on Bionate II [9] and it is unmeasured by the XRD (X-ray diffraction) methods due to amorphous character of substrate, thus the coupled computational and experimental method was proposed for determination of residual stresses in the coatings [8]. The introduction of Au interlayer changes a stress state in each layer of the material system TiN/Au/PU [3]. Particularly important is a change of sign of residual stress in the TiN from tensile to compressive. The presence of compressive stresses increases a toughness of connection that significantly decreases the probability of fracture [8].

On the other hand, numerical simulation allows us to investigate more comprehensively stress state of the VAD on macro and micro scales. The multi-scale model of VAD composed of multilayer materials [16] was developed and implemented into the FEM com-

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puter program [10]. The developed finite element code was verified on a macro scale by commercial code in [13] and by results of digital image correlation (DIC) in [15] for previous prototype of VAD [4] and its material.

In the above-mentioned numerical models, there was assumed a negligible influence of nano-layer coating on the overall stress and strain states of the VAD on the macro scale. This assumption is based on the fact that the thickness of the coating is much smaller than the thickness of the wall of the VAD's blood chamber. However, research made on deformation of bimetallic materials shows that in some cases, this effect can be significant, due to large surface area of coating [10]. For this purpose, in the present work, the DIC is used to estimate experimentally the influence of deposited heamocompatible coatings (gold and titanium nitride) on mechanical response of the ventricular assist device Religa Heart_Ext made of Bionate II under working conditions by comparison of the coated Religa Heart_Ext with the uncoated Religa Heart_Ext.

2. Materials and methods

The experiment of digital image correlation was prepared for two VADs of Religa Heart_Ext (Fig. 1) made of Bionate II and one of them was additionally coated by Au and TiN. The gold nano-coatings of thickness 5 nm were deposited as interlayers between the TiN and Bionate II. The gold was deposited by a magnetron sputtering method with a discharge current 10 mA and a deposition time 5 min. The TiN nano-coatings were deposited on the Bionate II substrates by using pulsed Nd:YAG laser system operating at the WIMiIP AGH [12]. The deposition process parameters were: 100 mJ energy of laser beam, 266 nm wavelength, 4.2 J/cm^2 fluence, 25 ºC temperature of substrate, 12 ns pulse duration at a repetition rate of 10 Hz and 5000 laser shots. The TiN coatings have thickness in the range of 30–35 nm. The introduction of Au interlayer between TiN and polymer changes a stress state in the material system. The Au interlayer helps to improve toughness of the materials' connection [8] and to increase the compressive residual stress in the coating, which results in reduction of stress and strain close to the boundary between the substrate and the coating. After deposition of the coating the components of Religa Heart EXT were assembled in accordance with technological process developed for clinically utilized VADs.

Fig. 1. The view of the Religa Heart_EXT

The DIC was applied for experimental investigation of the strains and displacements distribution on external surface of the blood chamber of VAD during loading. The theoretical basis of DIC is presented in [17], [18]. The experiment was conducted in a hydraulic system with water at operating temperatures of 25 and 37 °C, as well as under static pressures: 80, 120, 180, 220 and 280 mmHg, and static under pressures of: –25, –45, –75 mmHg. The subsequent images were taken after stabilization of pressure on a set level. A view of applied experimental system is shown in Fig. 2. The main parts of the experimental system are: VAD Religa Heart_EXT examined, heat exchanger with stabilization of temperature, commercial centrifugal liquid mixing pump (BP80, Medtronic) and pressure controller. The following components were also used in the experiment: the head Q-400 of Dantec Dynamics GmbH composed of two cameras CCD (1/1.8", 1624 × 1234 pixels) in stereoscopic system, light resources (LED) and ISTRA 4D software installed on laptop. The Religa Heart_Ext under examination was connected to the heat exchanger by means of medical drains (TYGON, 1/2" of diameter). In order to achieve thermal equilibrium a constant flow of water (0.1 l/min) is provided by the use of centrifugal pump. The stabilization of temperature was checked by using thermal imaging camera, which is presented in Fig. 3.

Two camera settings were used for each of the VADs under each loading and thermal condition. The first camera setting was applied to visualize the entire external surface of the VAD. The second camera setting was used to get better visualization of the selected area of VAD which is the zone between two connectors [11], because it is the most critical area of the system due to big values of strains [5]. Both camera settings are shown in Fig. 4, as well as the enlargement of the area between connectors presented for the coated VAD and achieved through the use of appro-

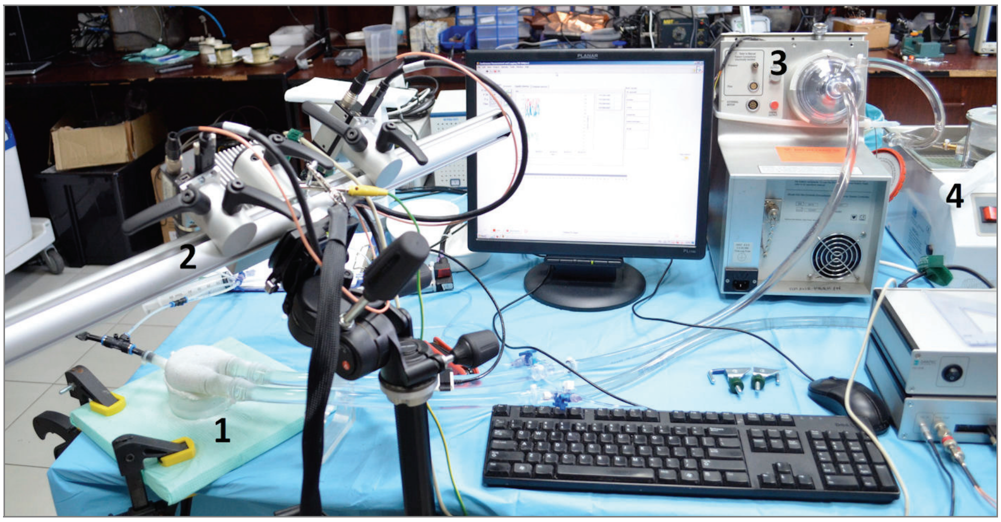

Fig. 2. The view of measurement system with marked elements:
1 – VAD examined, 2 – DIC system, 3 – centrifugal mixing pump, 4 – heat exchanger

priate lenses. The anticipated values of strain for the coated VAD are bigger and therefore, they are particularly important in the critical zone of coated VADs which is located between connectors.

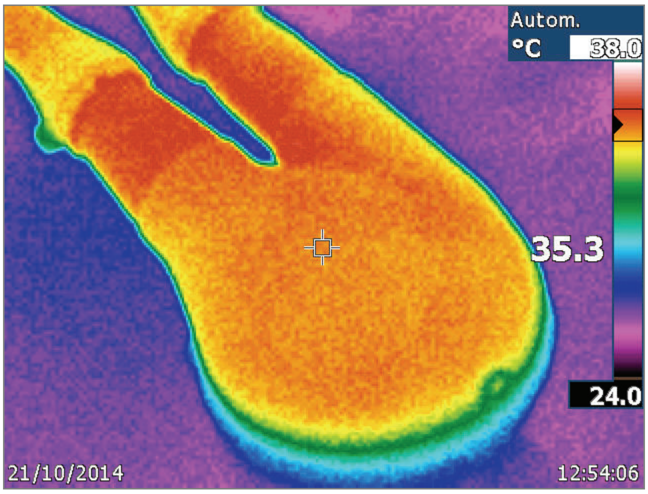

Fig. 3. The image recorded by infrared camera after stabilization at a temperature of 37 °C of uncoated Religa Heart_Ext

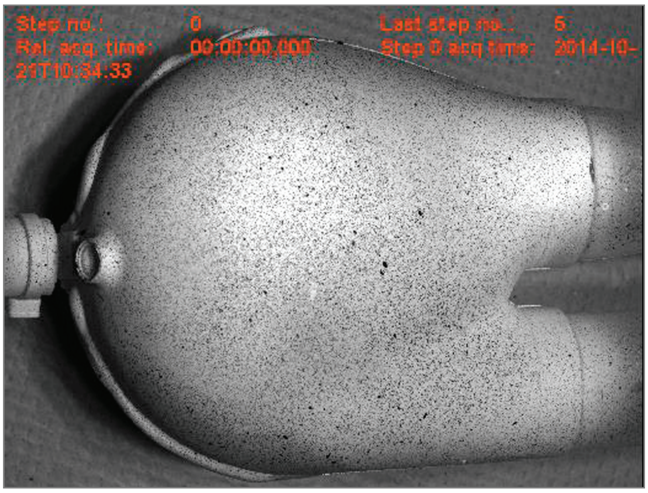

Fig. 4a. The first camera setting for the VADs

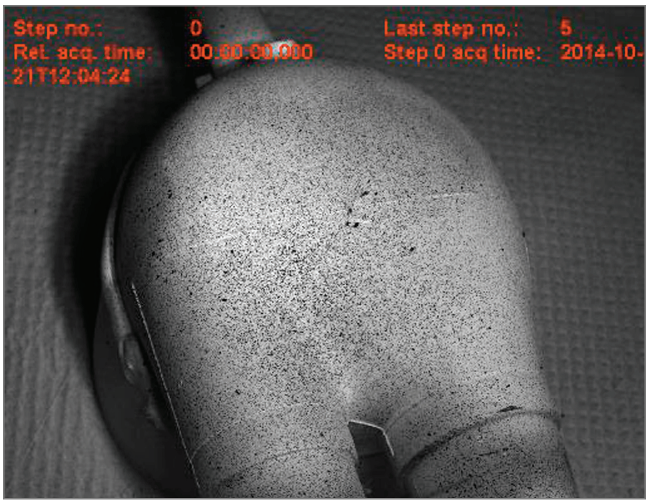

Fig. 4b. The second camera setting for the VADs

3. Results

In the present work, the analysis of results and errors was done for the highest value of pressure for both VADs at two temperatures and for two camera settings. The analysis of results (of strain and displacement distribution) and errors (standard deviations of strains and displacements) shows that the

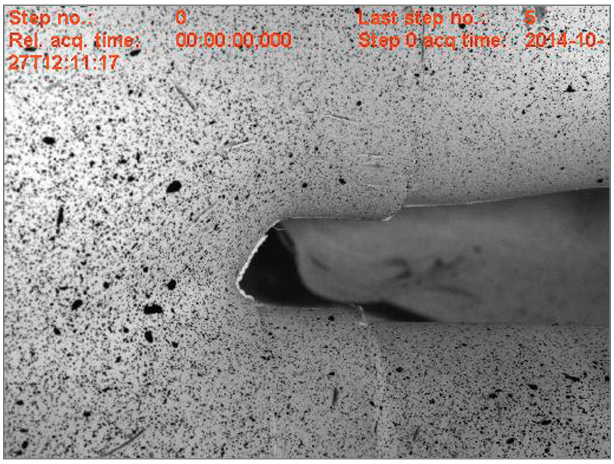

Fig. 4c. The enlargement of area between connectors of the coated VAD

Table 1. The maximum and minimum values of strains and displacements of the uncoated Religa Hart_Ext for the first camera setting and, at two temperatures under the maximum of loading 280 mmHg

	25 °C		37 °C	
Uncoated VAD	min	max	min	max
X-directional principal strain	–0.0058	0.0116	–0.0141	0.0152
Y-directional principal strain	–0.0049	0.0096	–0.0069	0.0118
X-directional displacement	–0.021 mm	0.19 mm	–0.28 mm	0.34 mm
Y-directional displacement	–0.01 mm	0.18 mm	0.03 mm	0.35 mm
Coated VAD	min	max	min	max
X-directional principal strain	–0.0056	0.0132	–0.0068	0.0158
Y-directional principal strain	–0.0046	0.0108	–0.0056	0.0127
X-directional displacement	–0.14 mm	0.12 mm	–0.063 mm	0.33 mm
Y-directional displacement	–0.6 mm	0.14 mm	–0.034 mm	0.25 mm
Enlargement of area between connectors of coated VAD			min	max
X-directional principal strain			–0.06	0.012
Y-directional principal strain			–0.04	0.013
X-directional displacement			–0.06 mm	0.16 mm
Y-directional displacement			–0.06 mm	0.22 mm

second camera setting (Fig. 4b) introduces bigger error. Thus, in the present work the comparison of VADs is presented on the basis of strains and displacement distribution only for the first camera setting at 37 °C (Figs. 5–7) and for the enlargement of area between connectors of the coated VAD at 37 °C (Fig. 8).

The maximum and minimum values of strains and displacements of the uncoated and the coated VADs at two temperatures for the first camera setting and for the enlargement of the area between connectors for the coated VAD at 37 °C are shown in Table 1.

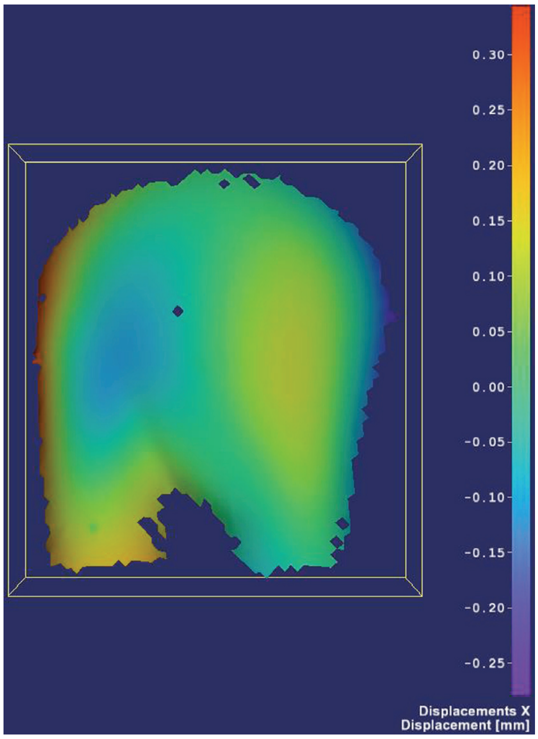

Fig. 5a. The uncoated VAD at 37 °C with distributions of *X*-directional displacement

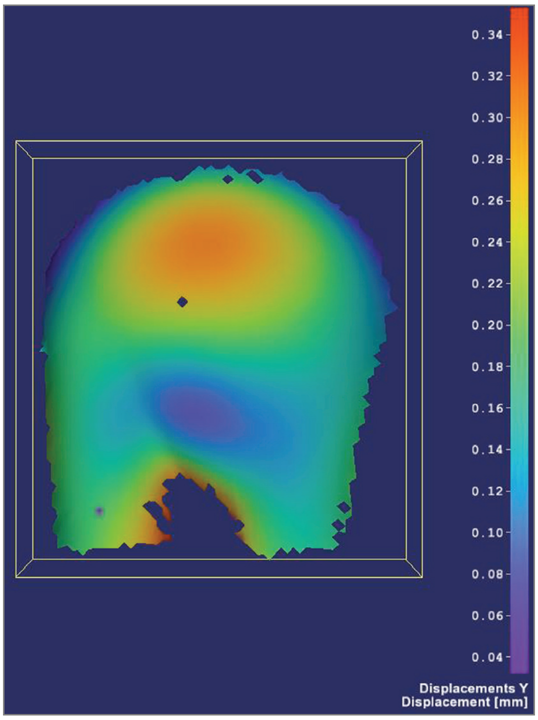

Fig. 5b. The uncoated VAD at 37 °C with distributions of *Y*-directional displacement

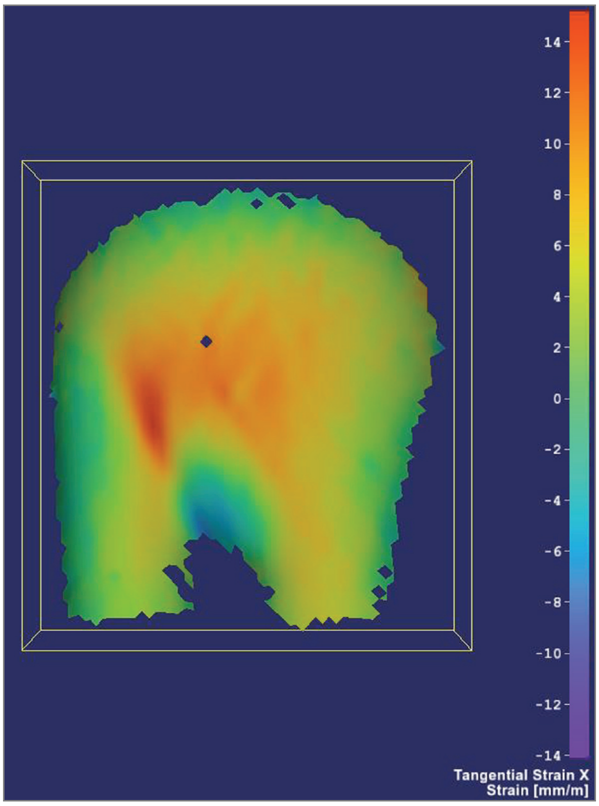

Fig. 5c. The uncoated VAD at 37 °C with distributions of *X*-directional principal strain (values × 10^{-3})

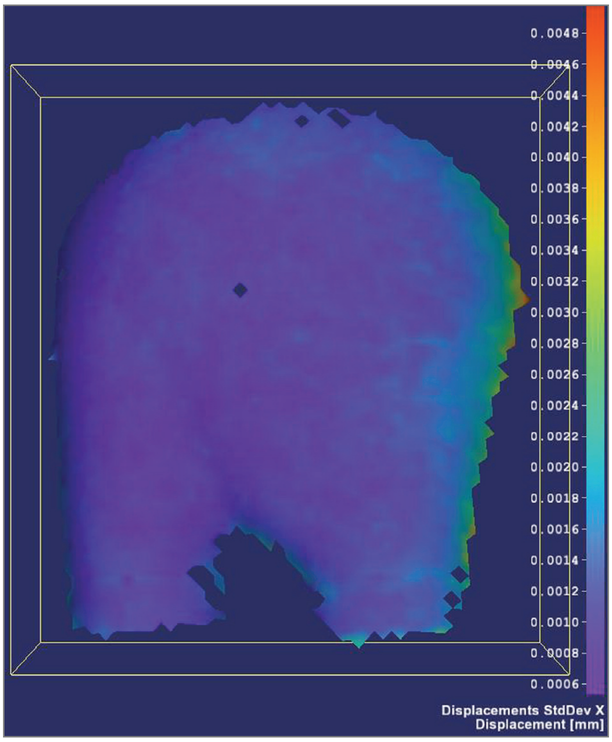

Fig. 6a. The distributions of standard deviations of uncoated VAD at 37 °C for *X*-directional displacement

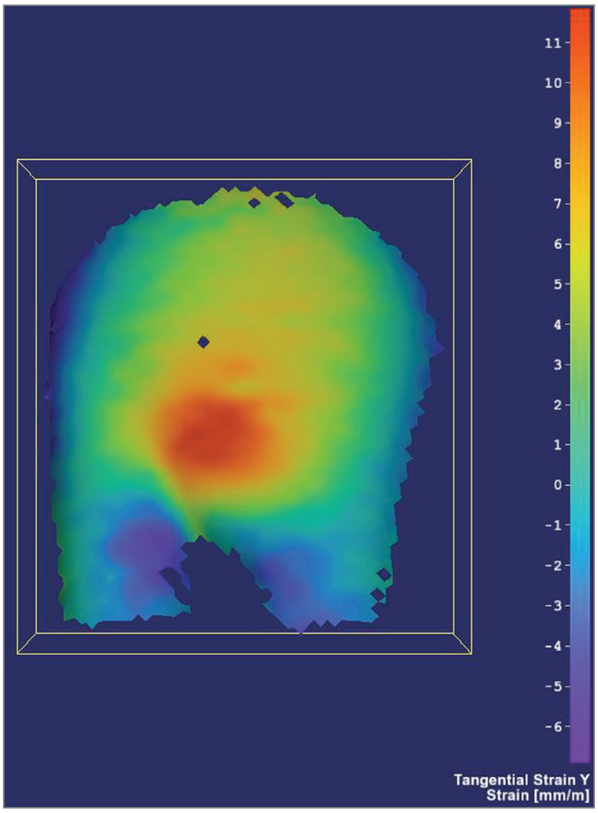

Fig. 5d. The uncoated VAD at 37 °C with distributions of *Y*-directional principal strain (values × 10^{-3})

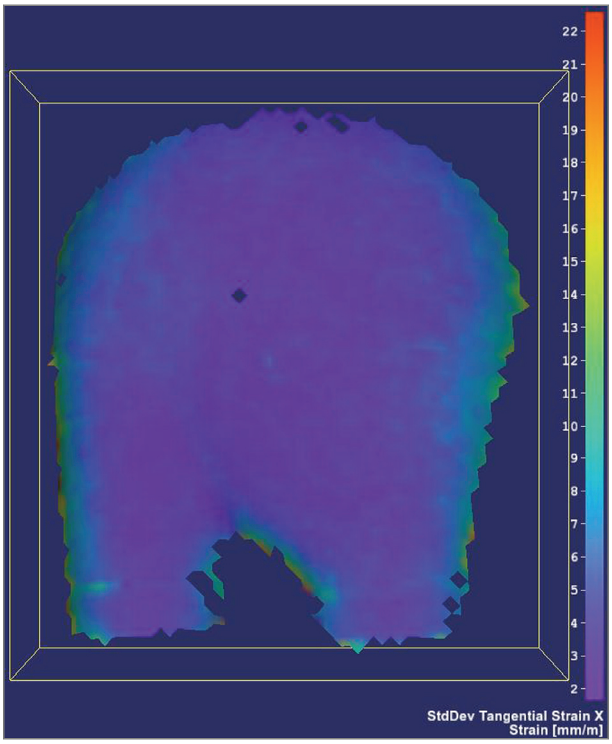

Fig. 6b. The distributions of standard deviations of uncoated VAD at 37 °C for *X*-directional principal strain (values × 10^{-3})

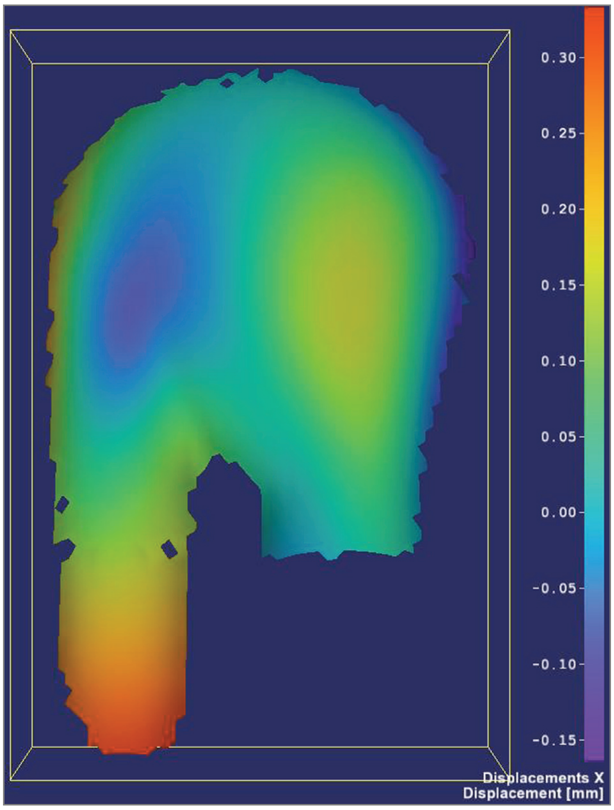

Fig. 7a. The coated VAD at 37 °C
with distributions of *X*-directional displacement

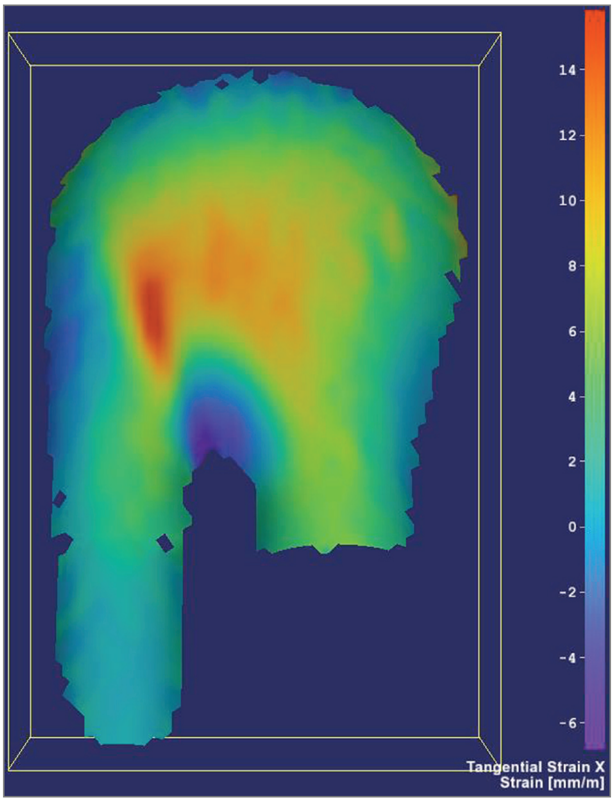

Fig. 7c. The coated VAD at 37 °C with distributions
of *X*-directional principal strain (values × 10^{-3})

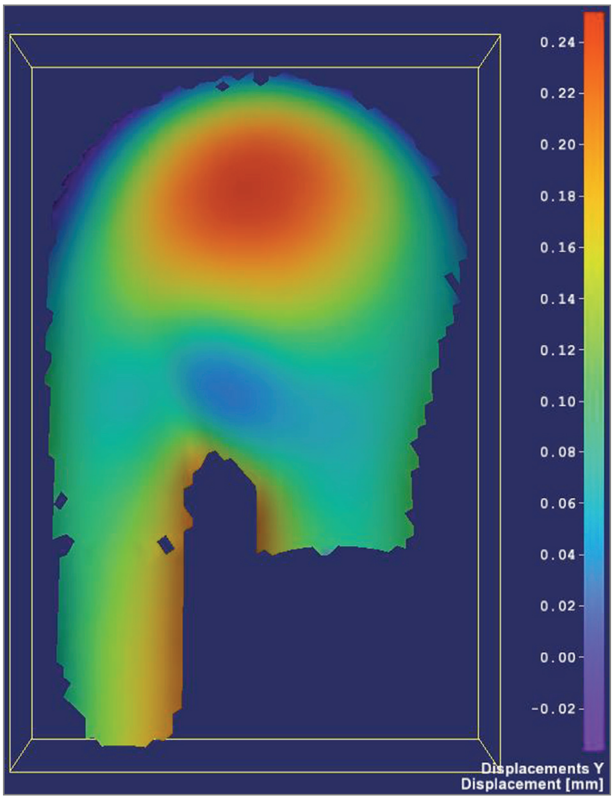

Fig. 7b. The coated VAD at 37 °C
with distributions of *Y*-directional displacement

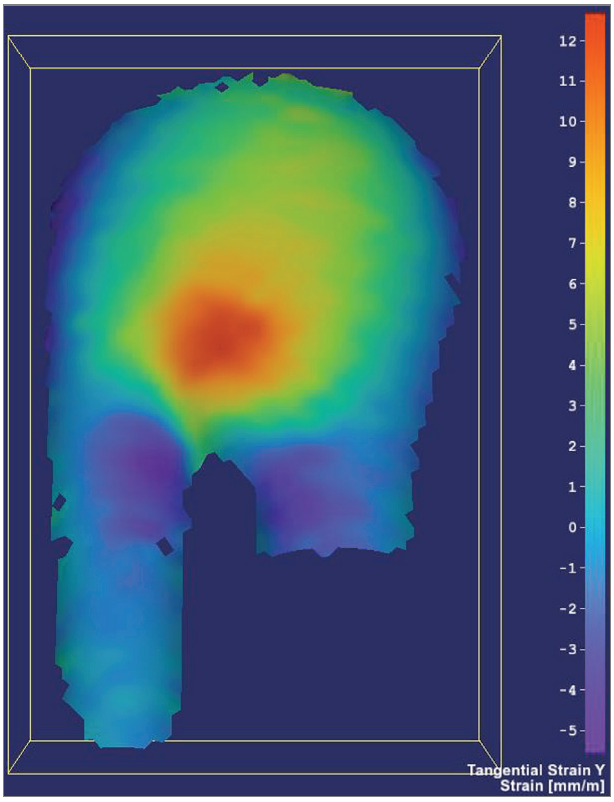

Fig. 7d. The coated VAD at 37 °C with distributions
of *Y*-directional principal strain (values × 10^{-3})

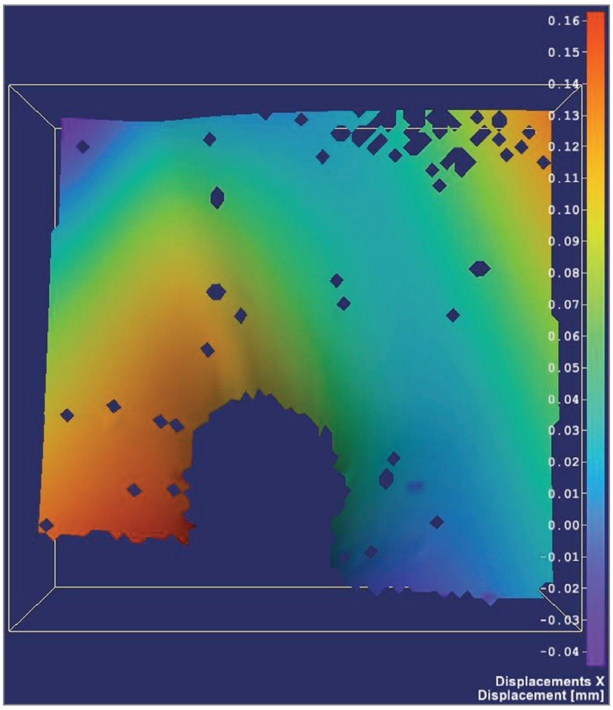

Fig. 8a. The enlargement of area between connectors of coated VAD at 37 °C with distributions of *X*-directional displacement

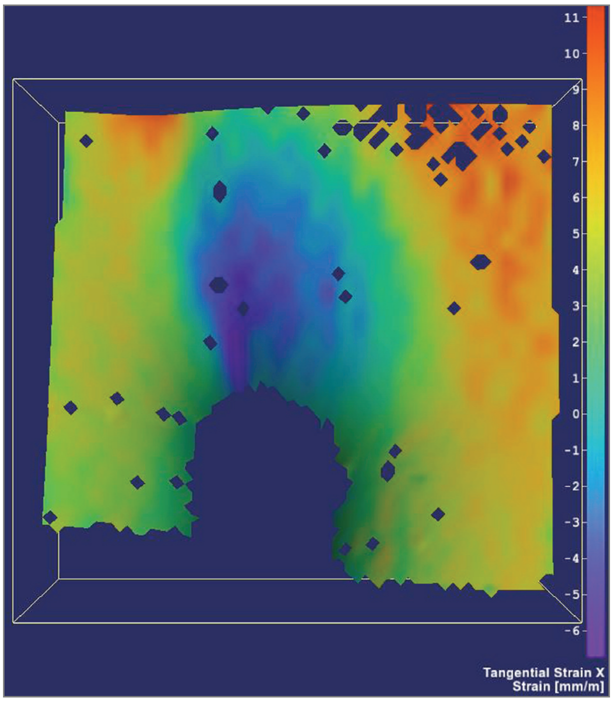

Fig. 8c. The enlargement of area between connectors of coated VAD at 37 °C with distributions of *X*-directional principal strain (values × 10^{-3})

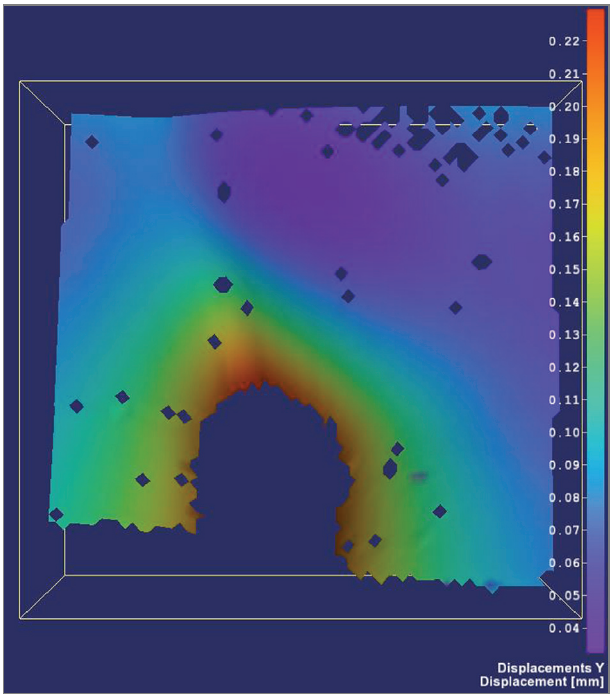

Fig. 8b. The enlargement of area between connectors of coated VAD at 37 °C with distributions of *Y*-directional displacement

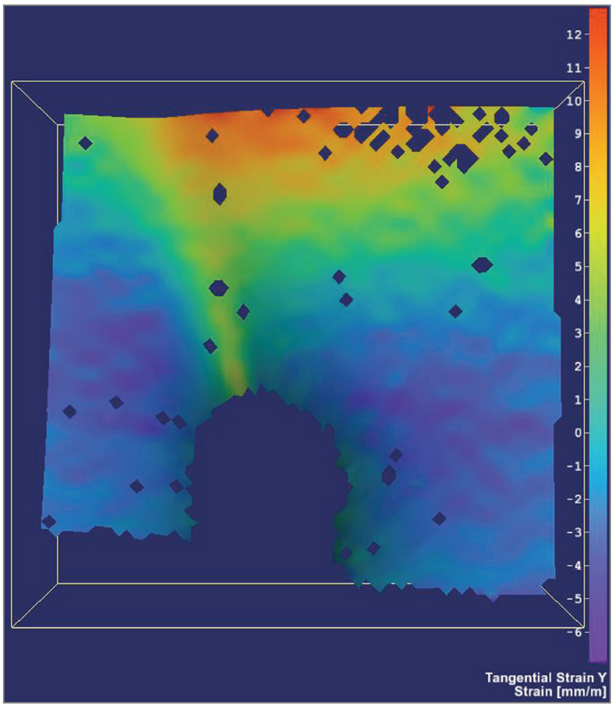

Fig. 8d. The enlargement of area between connectors of coated VAD at 37 °C with distributions of *Y*-directional principal strain (values × 10^{-3})

The errors calculated for the coated and the uncoated VADs at 37 °C, as well as for the enlargement of area between connectors for the coated VAD at 37 °C are presented in Table 2. The typical and representative distributions of errors (distributions of standard deviations) are shown in Fig. 6 for the *X*-directional displacement and for the *X*-directional strain for the uncoated VAD at 37 °C.

Table 2. The maximum and minimum values of standard deviations of strains and displacements of the uncoated and the coated Religa Heart_Ext, and of enlargement of area between connectors of the coated Religa Heart_Ext for the first camera setting at a temperature of 37 °C under the maximum of loading 280 mmHg

Uncoated VAD Standard deviation of	min	max
X-directional principal strain	0.00016	0.00226
Y-directional principal strain	0.00018	0.0014
X-directional displacement	0.00053 mm	0.005 mm
Y-directional displacement	0.0006 mm	0.0048 mm
Coated VAD Standard deviation of		
X-directional principal strain	0.00015	0.00083
Y-directional principal strain	0.00021	0.00056
X-direcitional displacement	0.00026 mm	0.0026 mm
Y-directional displacement	0.00059 mm	0.0034 mm
Enlargement of area between connectors of coated VAD Standard deviation of		
X-directional principal strain	0.000019	0.00058
Y-directional principal strain	0.000025	0.00039
X-direcitional displacement	0.00001 mm	0.00084 mm
Y-directional displacement	0.000016 mm	0.00014 mm

4. Discussion

The maximum of distributions of *X*-directional displacements are located on the right part of surface of the VADs and the minimum is located on the left part of the surface of the VADs. The distributions of *Y*-directional displacements have minimum located on the surface of VADs closer to the connectors and the maximum is located off-center of the chamber closer to the rear wall. The maximum of strains is located on the surface of VADs in the center of blood chamber. However, in the enlargement of area between connectors the distributions of strains and displacements have more irregularities, because the local distributions (Fig.8) show more precisely the heterogeneous character of the VAD surface.

The qualitative character of displacement and strain distributions for both VADs compared under different thermal and mechanical loadings is similar. The differences are only observed in values of calculated parameters. The percentage difference of strains between the coated and the uncoated VADs at 37 °C is 4–8%. The percentage difference of strains between the coated and the uncoated VADs at 25 °C is 12–14%. The analysis of values presented in Table 1 and shown as plotted distributions of parameters (Figs. 5, 7 and 8) proves that introducing the proposed system of coatings increases the strain on external surface of the coated VAD.

The comparison of results computed on external and internal surfaces of the uncoated blood chambers of previous versions of Polish VADs: POLVAD and POLVAD_EXT in [15] shows that the values of effective strains and stresses on external surface are smaller than on internal surface. This observation was in accordance with predictions, because the loadings are set to the internal surfaces. In the present work, the coated VAD is more deformable on external surface than the uncoated VAD. However, the correct interpretation of this observation can be done only after development of the FEM model of Religa Heart_Ext enriched with thin coating on its external surface considered as effective material layer. The proposed FEM model will show the distributions of strains and stresses on external and internal surfaces of the coated blood chamber of Religa Heart_Ext. The proper algorithms which are helpful to determine the external and the internal nodes of the VAD's FEM model have already been developed in [14].

The standard deviations of displacements computed with the application of the DIC's software at 37 °C are about 1.5% for the uncoated VAD and less than 1.5% for the coated VAD. The standard deviations of strains computed with the DIC's software at 37 °C are about 15% for the uncoated VAD and about 5% for the coated VAD. The standard deviations of displacements are less than 1% and the standard deviations of strains are less than 5% for the enlargement of area between connectors of the coated VAD. The application of appropriate lenses to get a better view of the area between connectors of the VAD leads to smaller values of errors. The errors for the calculated parameters (strains and displacements) of the coated VAD are smaller.

The disadvantages of digital image correlation method and sources of errors observed in the DIC's method were discussed for the previous versions of uncoated VAD in [15]. The sources of errors can be distinguished as follows:

(a) Roughness of the surface of blood chamber needed in measurement is caused by mechanically hand-applied paint. The paint of the blood chamber surface is not perfectly regular, it dries after certain time and then falls. The surface of blood chamber is not flat, has curves and irregularities and view of such a surface is taken by the cameras. It is impossible to register exactly the same location of points on such irregular surface. The blood chamber is permanently fixed in the experiment, but movements of the blood chamber are difficult to completely eliminate in the experiment. This is especially visible in distributions of small strains measured in DIC for smaller values of pressure, because bigger irregularities of strains distribution are obtained.

(b) The material of blood chamber is sensitive to temperature. It is impossible to heat uniformly the blood chamber by the water in the hydraulic system to temperature (37 °C) and to get the homogenous distribution of temperature on the external surface of blood chamber, because it is still in contact with environment (20–25 °C), (this is a typical temperature of environment for working VADs). It is also impossible to deform perfectly the blood chamber in all directions and to get uniform distribution of strain on the external surface by pressure which is set on the internal surface of the medical device.

In the present paper (in comparison with work [5]) the errors are minimized, among others, a different type of paint covering the external surface of the VAD is used, a different way of spraying black spots on its surface is introduced and the bottom part of the VAD is glued to the table to minimize movements of the VAD registered by the cameras.

5. Conclusions

– The selected research method – digital image correlation – helps to estimate influence of deposited coatings on mechanical response of ventricular assist device Religa Heart_Ext made of Bionate II under working conditions by comparison of the coated Religa Heart_Ext with the uncoated Religa Heart_Ext. The main result is an established fact that the thickness of nano-coating of 30 nm significantly affects deformation of the blood chamber on a macro scale.
– The proposed coating composition (Au and TiN) increases strain on external surface of the coated ventricular assist device.
– The second conclusion causes necessity of additional verification of mechanical response of the coated VAD, which is now subjected to short- and long-term fatigue tests in a hydraulic system. The specimens made of the material examined of the coated VAD will be analyzed in detailed micro-structural studies to estimate the influence of working conditions on coatings' morphology, occurrence of cracks and the possibilities of their application in the new versions of VAD's prototypes.

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