Hysteresis modeling of the porous nitinol delivery system, designed and fabricated by SLS method

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Abstract

At report, we presented a common design and theoretical modelling scheme for a porous scaffold from nitinol with a shape memory effect (SME), fabricated by the selective laser sintering (SLS) process. The operation of the SME fluidic MEMS involves such physical process as heat transfer, phase transformation with temperature hysteresis, stress-strain and electrical resistance variations accompanying the phase transformation. This model can be used for an estimation of drug delivery system (DDS) route during a porous volume changing.

Keywords: selective laser sintering (SLS); drug delivery systems (DDS); shape memory effect (SME); nitinol (NiTi intermetallics); micro-electro-mechanical system (MEMS)

1. Introduction

The intermetallic NiTi (named as nitinol) is widely known to have, even in a porous state, a high specific strength, corrosion resistance, damping characteristics and a unique shape memory effect (SME) [1]. It is the result of thermo-elastic martensite transformations that can take place inside its structure. The demonstrated biocompatibility of nitinol with its physical properties and SME, suggests that this material may offer substantial gains in orthopaedic implants and drug delivery systems (DDS) [2, 3]. To achieve these gains it is necessary to create implant elements capable of changing their shape after implantation due to the SME of nitinol that can be initiated at the temperature of a living organism. Especially in case of micro size it is not so easy to test a real prototyped MEMS device for optimizing design parameters. In order to make it easy to design these application devices of SME and to estimate performance of final products quantitatively, a CAD system should be indispensable. Although the CAD system needs

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numerical model to simulate the non linear behaviour of the fluidic MEMS under general stress and temperature conditions, there has been a little research for mathematical model especially useful for engineering.

The selective laser sintering (SLS) process has a great potential for engineering the implants, scaffolds, DDS with a prespecified and reproducible external and internal surface morphology that could be used in bio engineering applications [1-3]. A controllable internal structure of the interconnected porous channels allows providing of the drug release in the blood. The present report is dedicated to a functional design and a theoretical modelling of the porous DDS based on the laser-assisted-manufactured nitinol. Our modelling scheme is based on Dutta et al. and Ikuta et al. approaches [4, 8], which was developed for the SME wire actuator. In present case of the phase-change pumping, the driving pressure arises from the porous volume change due to the phase austenite - martensite transformation from one state to another under the temperature variation.

The remainder of the paper is organized as follows. Section 2 describes the functional design and modeling scheme for the nitinol DDS. Section 3 will present a theoretical model of thermal and permeability properties, an electrical resistance, a fraction volume for the each phase and stress-strain processes in the porous cylindrical nitinol sample during temperature changing in a living tissue. In Section 4, we present our conclusions.

2. Functional design and modelling scheme for the nitinol DDS

Since the laser synthesized 3D nitinol scaffolds (Fig.1) possess the SME [1], we recommend to regulate the drug release velocity by means of changing the pore sizes in the nitinol under the austenite - martensite phase transformation [2]. A typical martensite fraction (right axis) – temperature hysteresis schema is shown in Fig. 2. The phase transformation is characterized by the transformation start and finish temperatures: $A_s$ is the austenite start temperature, $A_f$ is the austenite finish temperature, $M_s$ is the martensite start temperature, and $M_f$ is the martensite finish temperature. This hysteresis is mainly caused by frictional effects associated with the movement of $A$-$M$ interfaces and $M$-$M$ interfaces with different crystallographic orientations of shape memory alloys (SMA) [5].

The thermo-mechanical SME, occurring in the course of the martensite transformation, is one of the attractive properties of some metallic materials [6]. This property explains the fact that it is possible to obtain the assigned form of the material, for example, the form of a spring by a special heat treatment.
Subsequently, after the cooling to the martensite condition (Fig. 2b), this spring can be plastically deformed, for example, preliminary expanded or compressed by the force $F_0$ (Fig. 2c). The subsequent heating of the material up to the austenitic state restores the initially assigned profile (Fig. 2d). Herewith, the force $F_1$ is generated inside the material that considerably exceeds the effort, required for its deformation, i.e., it is valid to say that the force $F_1 >> F_0$.

![Diagram](image)

**Fig. 3.** The porous 3D NiTi scaffold behaviour during the blood vessels flow

So during the heating stage (rise of the body temperature, curves a)-b)-d) in Fig. 2), the load of the stress condition in the NiTi takes place, the pore sizes decrease and biological solution is "extruded" from the pores (Fig. 3a). And at the cooling stage (the body temperature is reverted to its normal state, i.e. "a patient is recovered", curves d)-c)-a) in Fig. 2) the drug solution intake stops (Fig. 3b).

### 3. Theoretical model

#### 3.1. Basic assumptions

The amount of $A - M$ transformation is characterized by the martensite fraction $R_m$ (Fig. 2, axis from the right). Martensite fraction is defined as the volume fraction of martensite present in the SMA at any instant, therefore $0 \leq R_m \leq 1$. The austenite fraction can also estimate by the rule $R_a = 1 - R_m$ (where $R_m, R_a \in [0, 1]$) as the volume fraction of austenite present in the SMA. In general, at any given temperature, the phases $A$ and $M$ coexist. Obviously, the thermal, mechanical and electrical properties of SMAs can be predicted if the $R_m$ and the stress history of the SMA are known. Differential Scanning Calorimetry (DSC) is a well-known approach for analyzing phase transformations, and temperature hysteresis evaluation during the $A - M$ phase transformation [4, 7]. But Antonucci et al. brought out clearly in the [7] that an electrical resistivity (ER) measurement has proved to be a good probe for the identification of various phases in SMA, resulting more sensitive than conventional DSC technique in the phases evaluation and of its start and finish transition temperatures. As in our study [1], Antonucci et al. showed by the ER method the presence of the intermediate $R$- phase on the cooling stage during $A-M$ transformation.

Ikuta et al. [8] proposed the variable sublayer model to derive expressions for both strain and electrical resistance of the SMAs. The variable sublayer model hypothesizes that the SMA consists of parallel connected sublayers of different phases with different mechanical characteristics. Although the main three phases ($A - R - M$) are distributed randomly in the bulk metal from the microscopic point of view, it can be considered that their sublayers corresponding to each phase are connected parallel. They also proposed
a phenomenological algebraic model for a martensite fraction–temperature hysteresis. But later it has also been shown [4] that the hysteresis model developed in [8] is not suitable for simulation of a closed-loop control system. Yet one interesting approach was done in the Likhachev paper [9], where it was proposed a general differential model for representing SMA hysteresis minor loops, which is probably the first differential model of SMA hysteresis in the literature.

3.2. Heat transfer and permeability through a porous sample

Fig. 3 schematically shows the porous DDS from nitinol. The \( L_0 \) is the length and \( d_0 \) is the diameter of the undeformed DDS cooled to 100% martensite state and at zero pretension. If the \( \varepsilon_0 \) is the strain caused by initial deformation (Fig. 2c), while the DDS is still cooled to 100% martensite state, so the \( \varepsilon_r \) is the recoverable strain caused by \( M-A \) phase transformation. The total strain will be \( \varepsilon = \varepsilon_0 + \varepsilon_r \).

The balance of the heat energy governs the temperature of the SMA DDS. This must be essentially a transient heat transfer problem. We will consider that the internal resistance of the DDS to heat conduction is negligible compared to the convective heat transfer with the environment. We also assume that only natural convection occurs. Then, the temperature \( T \) of the porous SMA DDS is governed by the following convective heat transfer equation:

\[
\rho * c * \frac{dL_0}{4} \frac{dT}{dt} = \pi * d_0 * [ d_0 / 2 + L_h * (1 + \varepsilon / 2)] * h(T - T_{amb}) \pm \Delta H * \mu_v .
\]

where \( \rho \) - is a mass density of the porous SMA DDS, \( c \) – is a specific heat, \( h \) – a convection heat transfer coefficient, \( T_{amb} \) - a temperature at normal “healthy” state (~ 36.6 °C), \( \Delta H \) - a latent heat of the \( A \leftrightarrow M \) transformations, and \( \mu_v \) – is a specific molar volume of a new phase. We will consider that the above equation assuming that both \( h \) and \( c \) are constants. However in general, its temperature-dependent parameters and in future it could be use a polynomial interpolation for the temperature-dependent thermophysical properties of the porous SMA DDS also. Estimations show that for the simulation in this modelling study, the value of \( \varepsilon \) does not exceed 0.1. Thus we can propose a negligibility of the \( \varepsilon^2 \) term in (1). It is known that the \( M \rightarrow A \) transformation under a heating is endothermic, while the \( A \rightarrow M \) transformation under a cooling is exothermic. This observation is also taking into account of the heat transfer model (1).

The Darcy equation allows to calculate a permeability factor – \( K \) during a drug delivery process. With regard to contribution of deformation a liquid flow (blood flow) can be estimated by the next equation [10]:

\[
Q = \frac{K * \rho_v * g * \Delta H * S * P}{\mu_v * L * (1 + \varepsilon)^2} .
\]

where \( Q \) – is a liquid flow, \( \Delta H \) – a liquid level, \( g \) – a gravity acceleration, \( S \) – a sectional area of a filter element (DDS in our case), \( \rho_v \) – is a liquid density, \( \mu_v \) – a liquid dynamic viscosity and \( P \) – is a sample porosity. Under alternating deformation of DDS the liquid pulsation due to a pressure difference in its permeable structure will proceed. From equation (2) it is visible that the pulsation rate will depend not only pressure difference but on the size of the pores and the liquid viscosity also.
3.3. Martensite – austenite fraction and temperature hysteresis

The crystalline phase transformation between martensite and austenite, and hence the relationship between martensite fraction and temperature has a hysteretic character. In this section, we will use the special functions for the general differential hysteresis model based on the Likhachev approach [9]. We follow a phenomenological approach to hysteresis modelling also, which was proposed by Dutta et al. [4].

The typical $R_m - T$ hysteretic relationship for complete $A-M$ transformation was shown schematically in Fig. 2. Such hysteresis loop corresponding to complete $A-M$ transformation is called the major hysteresis loop. The area enclosed by the major hysteresis loop is called the hysteresis region. An incomplete $A-M$ transformation yields minor hysteresis loops within the major hysteresis loop. The underlying assumption is that the shape and transformation temperatures of minor loops are the same as those of the major loop [4, 8]. The shape of the minor loops is pertinent to hysteresis modelling of the SMA DDS because forward and reverse phase transformations can occur at any temperature within the hysteresis region while the DDS is in operation. However, in real situations the transformation temperatures $M_f, M_s, A_s$, and $A_f$ are not constant throughout and must be changed with the degree of porosity, presence of alloying elements in nitinol [1].

Dutta et al. proposed to use the Gaussian probability distribution functions (PDFs) $g(T)$ and $h(T)$ as the slope functions of the major hysteresis loop. The Gaussian PDF is characterized by the mean $\mu$ and the variance $\sigma^2$:

$$
\frac{dR_m}{dT} = \left\{ \begin{array}{ll}
\frac{\int h_{+}(T) + R_m - 1}{\int h_{-}(T) - h_{+}(T)} g_{+}(T), T \geq 0, \\
\frac{\int h_{+}(T) - h_{-}(T)}{\int h_{-}(T) - h_{+}(T)} g_{-}(T), T < 0,
\end{array} \right.
$$

(3)

where $R_m(0) = 1$ and subscripts $+$ and $-$ denote increasing and decreasing curves, respectively. Scaling constants for minor hysteresis loops given in (3) were originally proposed by Likhachev [9]. Fig. 4 shows the hysteresis loops obtained by the temperature profile (1). Under construction, we have assumed the martensite fraction at time $t = 0$ to be 1. This is a reasonable assumption, because the initial temperature of the DDS is “normal state” temperature, which means that the SMA DDS comprises 100% martensite at time $t = 0$. Hence, the solution of the last equation from the (3) gives the complete martensite fraction - temperature differential hysteresis model.
Ikuta et al [8] proposed to estimate the fraction volume by ‘logistic curve’ because of an integration of the DSC dependence curve is similar to a transformation ratio - temperature curve (R-T curve). So the major loop of A-M phase hysteresis accompanied with heating and cooling can be described by equation (4):

$$R_m(T) = 1/(1 + \exp[k_m(T - T_{0m})])$$

where in a cooling process $T_{0m} = (M_s + M_f)/2$ and $k_m = 6.20/(M_s - M_f)$. Then, there is $T_{0m} = (A_s + A_f)/2$ and $k_m = 6.20/(A_f - A_s)$ in a heating process. The coefficients in equation (4) were determined by adapting transformation temperature obtained from DSC chart in [8] and that from proposed there a logistic function model. The shape of a minor loop is similar to that of a major loop. Hence equation (4a) means the function for minor hysteresis loop.

$$R_m(T) = R_{ma}/[1 + \exp(k_m(T - T_{0m}))] + R_{mb}$$

(4a)

Similar reasoning can be made for the determining of the R – phase fraction also. Formula will be written down analogously equation (4-4a).

Above mentioned equations (3-4) have phenomenological basis [4, 8]. However, we can propose the own method for the phase fraction estimation by the experimental data from [1]. Converted fractions of each phase have been evaluated also using resistivity results (Fig. 5), where resistivity is a function of the temperature. In order to get an expression of converted phase as a function of $\rho(T)$, the mixing rule has been used, where the total resistivity has been considered as the sum of resistivity of each phase. In order to find an expression of the converted percentage for each phase, at first experimental resistivity data have been linearly interpolated in the temperature ranges where a single phase exists. Then, on the basis of the mixing rule for the resistivity, the following relationships for the phase fractions have been considered [7]:

$$R_i(T) = \frac{\rho(T) - \rho_j(T)}{\rho_i(T) - \rho_j(T)}$$

(5)
where $\rho$ - is the experimental ER, $i = (m$ or $r$ phases), $j = (a$ or $r$ phases), respectively. The equation (5) will express the martensite fraction decreasing (if $i = m$, $j = a$) during heating passing from 1 at a temperature lower than $A_s$ to 0 at a temperature higher than $A_f$. This equation will express respectively the martensite fraction increasing from 0 to 1 (if $i = m$, $j = r$), during cooling from $R$- phase and the $R$-phase fraction increasing from 0 to 1 (if $i = r$, $j = a$), during cooling from austenite phase.

3.4. Stress-strain relations

Martensite and austenite have very different stress-strain characteristics as it’s shown in Fig. 6 [8]. Therefore, the SMA DDS strain $\varepsilon$ is a function of both stress $\sigma$ and martensite fraction $R_m$. However, stress is caused by the DDS tension and can be expressed as a function of strain. We eliminate $\sigma$ from the $\varepsilon - \sigma - R_m$ relationship and derive $\varepsilon$ (note that $\varepsilon = \varepsilon^p + \varepsilon^y$) as an explicit function of $R_m$.

Mechanical properties of an austenite phase are modelled by a simple complete elastic body schematically shown in Fig. 6a. Because a practical SMA should be used under yield stress (i.e. elastic limit) not to introduce fatigue and will described Hooke's law. The $M$- phase has an elastic area under a low elastic limit and a plastic area caused by "twin deformation". It should be noted that the mechanism of the twin deformation completely differs from that of a regular plasticity based on the dislocation. Though dislocation is a kind of a slip mechanism and non-reversible, the twin deformation in a SMA is reversible one. Based on above reason, the mechanics of a $M$- phase can be described by the serial connection of an elastic part and plastic one with a limit strain of the twin deformation. The schematic model and stress-strain relationship are shown in Fig. 6b.

![Fig. 6. Stress – strain relations for: (a) austenite; (b) martensite](image)

Mechanical function is written in following equations:

$$\sigma_m(\varepsilon, \varepsilon^p_m) = E_m\varepsilon : |\varepsilon| < |\varepsilon^p_m + \varepsilon^y_m| \text{ (elastic area),}$$

$$= E_m\varepsilon^p_m : |\varepsilon| > |\varepsilon^p_m + \varepsilon^y_m| \text{ (plastic area)} \quad (6a)$$

where $\varepsilon^y_m$ is a elastic limit strain (an yield strain) of a $M$- phase. The similar approach could be use for a mechanical property of a $R$- phase also (if we decide to include its in our examination) modelled by the plastic and elastic part as shown in Fig. 6 b and a function can be rewritten in following equations:

$$\sigma_r(\varepsilon, \varepsilon^p_r) = E_r\varepsilon : |\varepsilon| < |\varepsilon^p_r + \varepsilon^y_r| \text{ (elastic area),}$$

$$= E_r\varepsilon^p_r : |\varepsilon| > |\varepsilon^p_r + \varepsilon^y_r| \text{ (plastic area)} \quad (6b)$$

where $\varepsilon^y_r$ is a elastic limit strain (an yield strain) of a $R$- phase. Since the each sublayer is connected
parallel, the total stress is divided by three phases as equation (6):

$$\sigma = R_a \sigma_a(\varepsilon) + R_m \sigma_m(\varepsilon, \varepsilon_m) + R_r \sigma_r(\varepsilon, \varepsilon_r)$$  \hspace{1cm} (6)$$

where $\sigma_a$, $\sigma_m$, and $\sigma_r$ mean the stress functions of the $A$, $M$- and $R$ phases.

There is known existence the "Clausius - Clapeyron like relationship" between stress and the transformation temperature, which expressed next form:

$$\frac{d\sigma}{dT} = \frac{\rho \Delta H}{T_0 \Delta \varepsilon}$$ \hspace{1cm} (7)$$

where $\rho$ – is a density, $\Delta H$ – is a latent heat, $T_0$ - transformation temperature under no stress, $\Delta \varepsilon$ - a strain due to phase transformation. It should be noted that common stress $\sigma^*$ which can contribute shift of transformation temperatures does not depend on the direction of stress macroscopically [8]. Hence $\sigma^*$ can be expressed by following equation:

$$\sigma^* = R_a |\sigma_a(\varepsilon)| + R_m |\sigma_m(\varepsilon, \varepsilon_m^p)| + R_r |\sigma_r(\varepsilon, \varepsilon_r^p)|$$ \hspace{1cm} (8)$$

Therefore basic equations on the transformation ratio including the effects of both stress and temperature can be added to dependences (8a) and (8b):

$$R_m(T, \sigma^*) = R_{ma} / \{ 1 + \exp(k_m (T - T_{0m} - c_m \sigma^*)) \} + R_{mb},$$ \hspace{1cm} (8a)$$

$$R_r(T, \sigma^*) = 1 - R_m(T, \sigma^*) / \{ 1 + \exp(k_r (T - T_{0r} - c_r \sigma^*)) \}$$ \hspace{1cm} (8b)$$

where the value of $k_m$ and $T_{0m}$ were determined by equation (4) in decreasing and in increasing processes. Above relationship is also available in shear stress fields.

3.5. Electrical resistance relations

The ER of austenite and martensite are different [1, 4, 7, 8]. Thus the electrical resistance of the SMA DDS in any given state depends on the martensite fraction $R_m$ in that state. At the same time, the resistivity of each phase is also a function of the temperature (Fig. 5)) [1, 4]. We use the variable sublayer model [8] to model the electrical resistance of SMA DDS.

$$R^*(T) = \frac{4 L_0 (1 + 2 \varepsilon)}{\pi l_0^2} \rho_a(T), R^n(T) = \frac{4 L_0 (1 + 2 \varepsilon)}{\pi l_0^2} \rho_m(T),$$ \hspace{1cm} (9)$$

Where Ra - electrical resistance of 100% austenite, Rm - electrical resistance of 100% martensite, $\rho_a(T)$ - electrical resistivity of austenite, and $\rho_m(T)$ = electrical resistivity of martensite. Using the variable sublayer model [8], the two phases can be considered to be in parallel. Then the common electrical resistance of the DDS is given by

$$\frac{1}{R(T)} = \frac{(1 - R_m)}{R^*} + \frac{R_m}{R^n}$$ \hspace{1cm} (10)$$
Substituting for \( R^e \) and \( R^m \) from (9), we obtain the following expression for \( R \):

\[
\frac{1}{R(T)} = \frac{\pi d_o^2}{2L_o(1+2\varepsilon)} \left[ \frac{1-R_m}{\rho_e(T)} + \frac{R_m}{\rho_a(T)} \right] \tag{11}
\]

Ikuta et al. [8] modelled the resistivities as linear functions of temperature. However, we known that the nonlinear expressions for the resistivities satisfy experimental results [1]. Total resistivity of SMA can be estimated as a linear summation of resistivities of each phase as following equation:

\[
\rho = R^p\rho_p^* + R^m\rho_m^* + R^r\rho_r^* \tag{12}
\]

where \( \rho_p, \rho_m \) and \( \rho_r \) mean the ER of \( A \)- phase, \( M \)- phase and \( R \)- phase respectively. Hence, the austenite and martensite resistivities could be obtained from equations (9-11). Consider Fig. 4, which shows \( R_m \) as a function of \( T \). Suppose \( T \) increases from \( M_f \) to \( A_r \). We know that \( R_m = 1 \) in this region. Hence, the electrical resistance \( R \) would only depend on \( \rho_m \), and \( \rho_m \) should take a form which would yield the shape of the increasing curve in Fig. 5. Similarly, suppose \( T \) decreases from \( A_f \) to \( M_s \). Then \( R_m = 0 \), and \( \rho_a \) should take a form which would yield the shape of the decreasing curve in Fig. 5. The above reasoning explains qualitatively why the temperature dependence of resistivities of each phase is as shown in experimental dependence Fig. 5. Having obtained \( R \) as a function of \( R_m \) and \( T \), we will use the hysteresis model developed in Section 3.3 to model the SMA wire resistance vs temperature relationship.

4. Conclusion

In the present work, a common design and theoretical modelling scheme are sketched out. Deformation and stress produced in NiTi must create a useful displacement and occurrence of the force necessary for the drug release from the pores. We developed a complete mathematical model for the porous SMA DDS device. The model is capable of simulating the temperature, martensite fraction, stress, strain and electrical resistance of the bio fluidic MEMS.

The basic stages of the DDS functioning are connected with a complete or incomplete martensite transformation at the body temperature level. The SME temperature range shifting and temperature increasing-decreasing during a disease evolution gives the possibility to govern and regulate the distance between the structural components (pore sizes) and to use the drug dosed supply in the blood. In our opinion, micro devices of this type can be used repeatedly.

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