MULTIPHYSICAL ASPECTS OF SHAPE MEMORY ALLOY ACTUATOR

Peter Drahoš, Vladimír Kutiš

Institute of Automotive Mechatronics,
Faculty of Electrical Engineering and Information Technology,
Slovak University of Technology in Bratislava, Bratislava, Slovak Republic
E-mail: peter.drahos@stuba.sk, vladimir.kutis@stuba.sk

Received 05 May 2017; accepted 24 May 2017

1. Introduction

Shape Memory Alloy is a smart material converting thermal energy to mechanical work, which can be used in many different mechatronic systems [1, 2] like actuator. The thermal actuator made of Nickel–Titanium (NiTi) wire is heated by Joule loss heat caused by electric current and naturally air-cooled. Critical part of SMA actuator from thermal point of view is connection NiTi wire to crimp - see Fig. 1. This part of NiTi wire is cooled more than the rest of the wire due to connections to crimp. It is necessary to investigate the influence of actuator crimps to temperature distribution along NiTi wire, because unsuitably designed connection can caused loss of power and other characteristics in this part of SMA actuator.

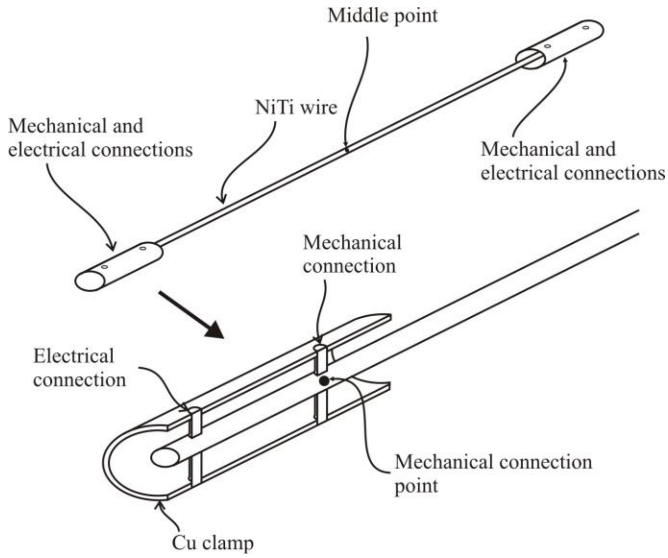

Fig.1: *SMA actuator with clamp.*

2. SMA actuator lumped model

Typical distribution of temperature along the NiTi wire is shown in Fig. 2. This distribution can be also obtained by solving differential equation of heat transfer with appropriate boundary conditions including temperatures T_1 and T_2 - this model is called lumped model. To model the distribution of temperature along NiTi wire using differential equation, it is necessary to know the maximum temperature of NiTi wire denoted as T_P - this temperature is developed as potential of Joule loss heat ($P = R_e I^2$) and temperatures T_1 and T_2 in both connection points, respectively. The temperature of Cu body of clamp was considered close to the temperature T_1 of electrical contact due to very good thermal conductivity of anchor. The direction of thermal flows from NiTi wire to both connections are shown by red arrows in Fig. 2. The variables and parameters used in next equations are summarized in the Tab.1.

Tab. 1. *Variables and parameters used in analysis of SMA.*

T_0 [°C]	Ambient temperature	d [m]	Diameter of NiTi	α [Wm^{-2}°C^{-1}]	Convection coefficient
T_1 [°C]	Temperature - point of electrical conection	S [m^2]	Cross-section	λ [Wm^{-1}°C^{-1}]	Thermal conductivity
T_2 [°C]	Temperature - point of mechanical connection	A[m^2]	Convective surface	c [J kg^{-1}°C^{-1}]	Specific heat
T_b [°C]	Temperature of clamp	V[m^3]	Volume	R [°C W^{-1}]	Thermal resistance
T_P [°C]	Temperature potencial NiTi – midle point	L [m]	Length	τ [s]	Time constant
x [m]	Distance	a[m^{-1}]	Coefficient	P [W]	Thermal power

In the case that electric current, which is used as thermal power source, is constant or is varied very slowly (i.e. the system is considered steady-state), the distribution of temperature can be described as following ordinary differential equation [5]

$$\frac{d^2T}{dx^2} - \frac{\alpha A(T-T_0)}{\lambda V} = -\frac{P}{\lambda V} \tag{1}$$

with boundary conditions (see Fig. 2, PART1, PART2): electrical connection point: $T(0) = T_1$, mechanical connection point: $T(L) = T_2$. The particular solution of the equation (1) is

$$T(x) = C_1 e^{-ax} + C_2 e^{ax} + C_3 \tag{2}$$

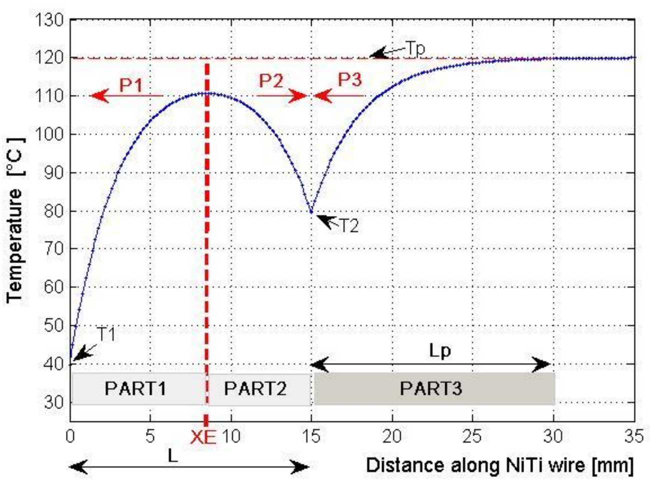

Fig. 2: *The distribution of temperature along NiTi wire with boundary temperatures T_1 -electrical connection, T_2 -mechanical connection and T_P –middle point*

where the coefficients a, C_1 , C_2 and C_3 are:

$$C_1 = \frac{(T1-T2)-C_2\left(1-e^{aL}\right)}{1-e^{-aL}} \tag{3}$$

$$C_2 = \frac{(T_1-C_3)\left(1-e^{-aL}\right)-(T_1-T_2)}{e^{aL}-e^{-aL}} \tag{4}$$

$$C_3 = T_0 + \frac{P}{\lambda V a^2} = T_0 + \frac{P}{\alpha A} = T_P \tag{5}$$

$$a^2 = \frac{\alpha A}{\lambda V} = \frac{4\alpha}{\lambda d} \tag{6}$$

The „*1/a*“ [m] - see coefficient a^2 in (6) is characteristic length and depends on material, convection coefficient α and geometry of SMA wire. The distance L between two anchor points will be viewed in relation to the $1/a$. T_P is the potential temperature according to (5).

Above mentioned solution of equation (1) is valid for all length L, but for length $L > 4{,}6/a$ the solution (2) can be simplified and the expression e^{-aL} can be crossed out. This simplification represents error less than 1%. Other simplification can be carried out for cases, where the length L is too large, for example for $L \geq 10/a$. For these cases, the influence of coefficient C_2 on the solution is relatively small, so we can set $C_2=0$ and then the temperature distribution have form:

$$T(x) = T_P - (T_P - T_2)e^{-ax} \tag{7}$$

The boundary conditions are mechanical connection point: $T(L) = T_2$ and middle point $T(L_P \geq 10/a) = T_P$. Equation (7) describes part of the curve marked PART3 in Fig. 2.

3. Electro-thermal analysis

The goal of steady-state electro-thermal analysis is to calculate the spatial temperature distribution on SMA actuator and special attention is paid to temperature distribution in NiTi wire near mechanical connection, where the influence of different thermal conductivities of mechanical connection is analyzed see Fig. 1. Also transient electro-thermal analysis is performed in order to investigate thermal dynamics of SMA actuator. NiTi wire has diameter 0.3 mm and the active length of actuator is 100 mm - this is the length between two mechanical connections. The length of clamp is 11 mm and the inner and the outer diameter of clamp is 1.5 mm and 2 mm, respectively. Screw diameter of mechanical and electrical connection is 0.4 mm. Considered electrical and thermal material parameters of NiTi wire, which are function of temperature and they are defined in Tab. 2. Because not only steady-state but also transient analysis was performed, thermal capacity and density of NiTi wire has to be included into material model.

Tab. 2. *Electrical and thermal material parameters of NiTi wire.*

Martensite to Austenite, increasing temperature	[°C]	0	119	129	180
Austenite to Martensite, decreasing temperature	[°C]	0	69	81	180
Thermal conductivity	[W/m°C]	8	8	18	18
Electrical resistivity x10^8	[Ωm]	76	76	82	82

Both material properties were considered as constant in all investigated thermal conditions. Thermal capacity of NiTi wire has value 460 J/kg°C and density of NiTi wire is 6540 kg/m^3. All other components - clamp, screws for mechanical and electrical connections were considered with constant material properties - see Tab.3. Clamp and screws for electrical connection is made of copper. In order to investigate the influence of mechanical connection, thermal conductivity of screws for mechanical connection is considered in some range - from 0.5 W/m°C to 2 W/m°C. Other thermal and electrical material parameters of screws for mechanical connection were compatible with material properties of teflon. In the inner space of clamp, there was considered air with constant thermal properties - thermal conductivity 0.02 W/m°C, thermal capacity 700 J/kg°C and density 1.2 kg/m^3.

Tab. 3. *Electrical and thermal material parameters of clamp and connections.*

Component	Material	Thermal conductivity	Electrical resistivity	Thermal capacity	Density
		[W/m°C]	[Ωm]	[J/kg°C]	[kg/m^3]
Mechanical connection		0.5/1 /2	1x10^{12}	1000	2100
Electrical conn. & clamp	copper	385	1.67x10^{-8}	396	8900

4. FEM simulation

Electro-thermal steady-state and transient analysis of SMA actuator was performed by code ANSYS Multiphysics.

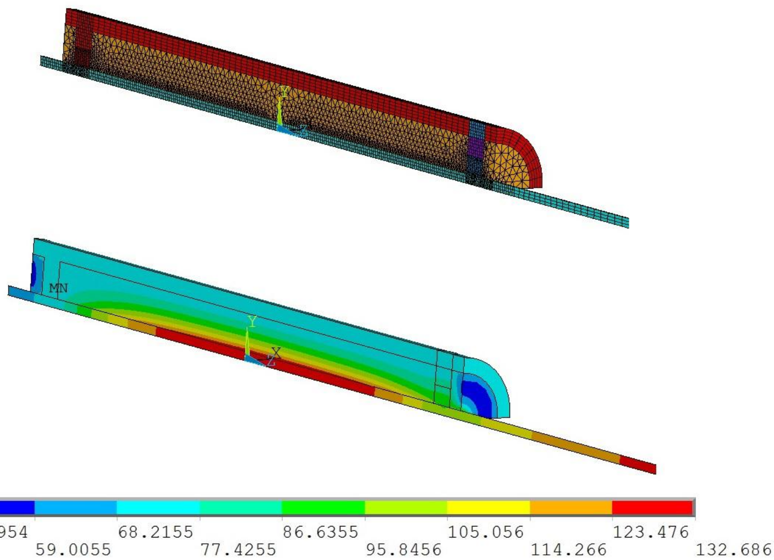

Fig. 3: *Top -mesh of actuator, Bottom -temperature distribution near mechanical connection.*

Due to symmetry of actuator and connections only 1/8 of geometry model was considered - see Fig. 3 Top. There were used 2 element types, 3D solid element for coupled analysis SOLID 226, where electro-thermal capabilities were set up and 2D surface effect element for convection and radiation heat transfer SURF 152. Boundary conditions were prescribed as follows:

- electrical boundary conditions - electric current, that flows from clamp through electrical connection to NiTi wire had value 0.8 A and in transient analysis starts at time 0.01 s
- thermal boundary conditions - convection was prescribed in all outer surfaces of NiTi wire and clamp. The coefficient of heat transfer by convection was calculated analytically separately for outer cylindrical surface of NiTi wire and separately for clamp. All analytical calculations were performed for horizontal configuration of SMA actuator using dimensionless parameters. Calculated coefficients of heat transfer were included in the were included in the model as a function of surface temperature. Ambient temperature was 27 °C.

In steady-state thermal analysis, three analyses with different thermal conductivities of mechanical connection were performed. Longitudinal distributions of temperature in active part of NiTi wire for all three thermal conductivities of mechanical connection are shown in Fig. 4 Left. As we can see from this figure, if material of mechanical connection has thermal conductivity 2 W/m°C or 1 W/m°C, not all points of NiTi wire reach starting transformation temperatures. If we consider that thermal conductivity of mechanical connection is 2 W/m°C, than almost 16% of NiTi wire length does not cross finish phase change temperature. The spatial temperature distribution in NiTi wire and also in clamp and in connections for thermal conductivity of mechanical connection with value 2 W/m°C is shown in Fig. 3 Bottom. As we can see from the Fig. 3 Bottom and from Fig. 4 Left, mechanical connection can strongly affect of NiTi wire temperature near mechanical connection.

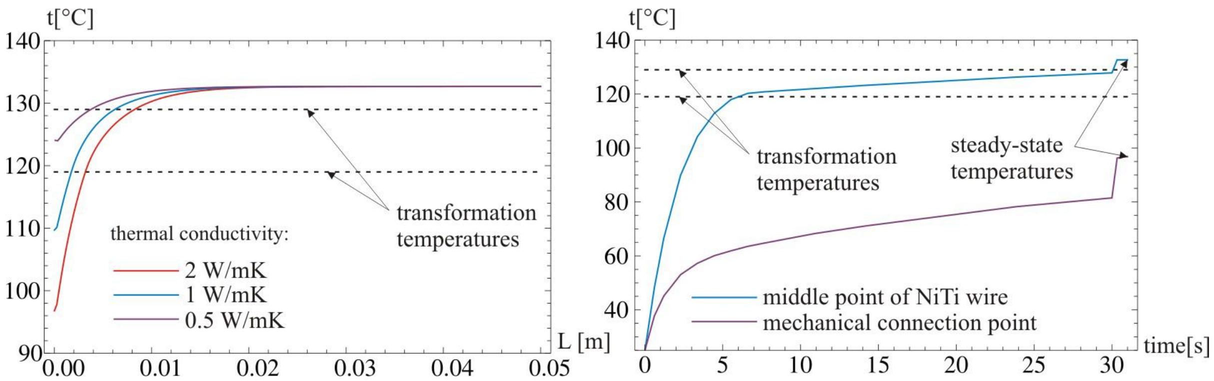

Fig. 4: *Left - Longitudinal distributions of temperature in active part of NiTi wire for all three thermal conductivities of mechanical connection, Right - thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 2 W/m°C.*

Fig. 4 Right and Fig. 5 Left and Right shows thermal dynamics of NiTi actuator. As we can see from all three graphs, after 30 seconds the middle point of NiTi wire (see Fig.1) almost reaches the finish phase change temperature for all three investigated thermal conductivities of mechanical connection, but NiTi wire near mechanical connection does not cross even start phase change temperature after 30 second.

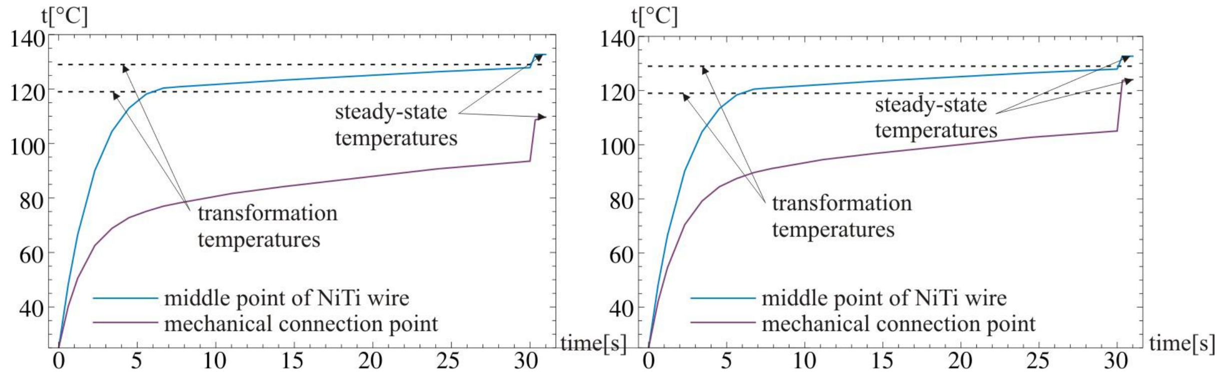

Fig. 5: *Left - thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 1 W/m°C, Right - thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 0.5 W/m°C.*

5. Conclusion

Coupled electro-thermal analysis of thermal SMA wire actuator made of Nickel-Titanium alloy was presented in the paper. The goal of the paper was focused on analysis of temperature distribution near mechanical connection of NiTi wire. In the paper steady-state and transient electro-thermal analysis of NiTi wire was presented.

Acknowledgement

This work was supported by Grant Agency VEGA, grant No. 1/0228/14 and 1/0453/15, by the grant KEGA-011STU-4/2015 and by the Slovak Research and Development Agency under the contract No. APVV-14-0613.

References:

[1] J. L. Pons: Emerging Actuator Technologies. John Wiley & Sons Ltd. 2005, West Sussex England (2005).
[2] Schwartz, M. Encyclopedia of Smart Materials, John Wiley&Sons, (2002).
[3] ANSYS Theory manual, (2014).
[4] Auricchio, F., Scalet, G. and Urbano, M. A Numerical/Experimental Study of Niti-nol Actuator Springs. Journal of Materials Engineering and Performance (2014)
[5] Eliáš J. Horváth J. Kajan J. Zbierka úloh z vyššej matematiky 3. Alfa Bratislava. 1980. 220 pp.
[6] P. Drahoš, V. Kutiš: Design and Simulation of SMA Actuator. *International Review of Automatic Control*, **4**, 588, (2011).