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ELECTRO-THERMO-MECHANICAL ANALYSIS OF SMA ACTUATOR

VLADIMÍR KUTIŠ*, PETER DRAHOŠ*, JUSTÍN MURÍN*, JURAJ PAULECH* AND JURAJ HRABOVSKÝ*

*Institute of Automotive Mechatronics
Faculty of Electrical Engineering and Information Technology
Slovak University of Technology in Bratislava
81219 Bratislava, Slovak Republic
e-mail: vladimir.kutis@stuba.sk, web page: http://www.fei.stuba.sk/

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Abstract. The paper deals with electro-thermal and structural analysis, modeling and simulation of the Shape Memory Alloy (SMA) actuator made of Nickel-Titanium alloy. Primary goal is focused on electro-thermal analysis and investigation of SMA actuator temperature distribution near mechanical connection. The secondary goal is focused on actuation deformation and the influence of nonhomogenous temperature distribution on the deformation of SMA actuator. All analyzes are performed by finite element code ANSYS.

1 INTRODUCTION

Shape Memory Alloy (SMA) is a smart material converting thermal energy to mechanical work, which can be used in many different mechatronic systems like actuators as well as sensors [1, 2]. Transformation behaviour exploited in SMA material is thermally induced shape change, often labeled the shape-memory effect. A material component may be deformed or strained at low temperatures and when heated, it reverses this strain and remembers its prestrained shape. Deformable martensite phase transforms to a more stable austenite phase at higher temperatures. Thermally activated SMA applications require temperature control to optimize the effect of shape memory. Typical application areas of SMA are aerospace industry – composite structures that have SMA wires embedded can be used to change the shape of an airplane wing; vibration damper systems – vibrational dampers, comprised of composite materials using prestrained, embedded SMA wire; medical applications – medical applications use the superelastic property of SMA, and many of them are in the expanding field of minimally invasive surgery.

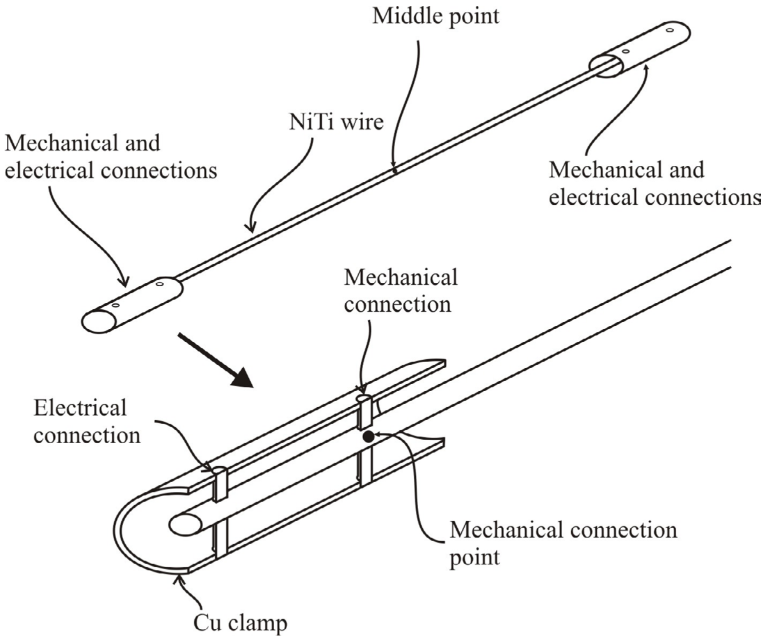

Figure 1: SMA actuator with clamp

The paper deals with coupled electro-thermo-structural analysis of thermal SMA wire actuator made of Nickel-Titanium (NiTi) alloy in FEM code ANSYS [3] – see Fig 1. The main idea of thermal SMA actuators is to cross transformation temperature from martensite phase to austenite phase and than required actuation deformation of SMA actuator is induced by this phase change. Both phases from electro-thermal viewpoint have different electrical and thermal material properties and there is also latent heat during phase transformation. Phase change is not performed at one temperature but there is temperature range where the one phase is transformed to other. Start and finish temperature of phase change depends on mechanical stress of NiTi wire as well as on increasing or decreasing of temperature, i.e. heating or cooling of NiTi wire.

Investigated SMA NiTi wire actuator is loaded by external force which causes axial stress in NiTi wire with value 200 MPa. The transformation of martensite phase to austenite phase (i.e heating process) in investigated SMA wire under tensile stress 200 MPa starts at temperature 119 °C and finishes at temperature 129 °C. In the reverse cooling process, where austenite phase transforms to martensite phase, the transformation under the same stress conditions starts at temperature 81 °C and finishes at temperature 69 °C. In martansite phase under transformation temperature and under prescribed mechanical loading, the strain of SMA wire has value 4.8% and in austenite phase (i.e over the transformation temperature) the strain has value 0.4%. These values in real system and in modeled approximation in material model are shown in Fig. 2.

NiTi actuator is loaded through mechanical connection and actuation motion is performed by heating up of actuator. Active length of NiTi wire is length between two

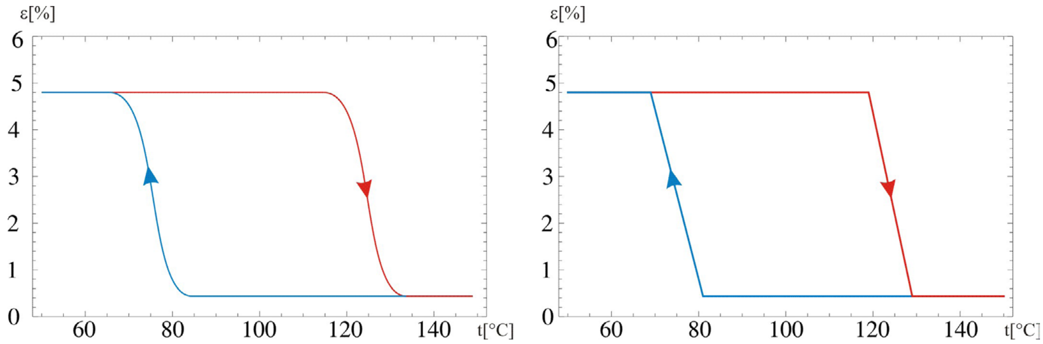

Figure 2: Transformation temperatures during the phase change, Left – real behaviour, Right – modeled approxiamtion in material model

mechanical connections – see Fig. 1. SMA wire is heated by Joule loss heat caused by electric current that is passing through the NiTi wire through clamp and electrical connection. System is naturally cooled by surrounding air.

Critical part of SMA actuator from thermal and also mechanical point of view is mechanical connection of NiTi wire to clamp. This part of NiTi wire is cooled more than the rest of the wire due to connections to clamp. It is necessary to investigate the influence of actuator clamps and specially mechanical connection to temperature distribution along NiTi wire and its effect on actuation deformation of SMA wire, because unsuitably designed connection can cause loss of power or smaller actuation deformation and other characteristics in this part of SMA actuator.

2 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 analysed – see Fig. 1. Also transient electro-thermal analysis is performed in order to investigate thermal dynamics of SMA actuator.

2.1 Geometry and material parameters

Geometry of NiTi wire with clamp is shown in Fig. 1. In this figure, there is also shown mechanical and electrical connections.

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 are defined in Tab. 1. Because not only steady-state but also transient

Table 1: Electrical and thermal material parametrs of NiTi wire as function of temperature

Martensite to Austenite [°C] (Increasing temperature)	0	119	129	180
Austenite to Martensite [°C] (Decreasing temperature)	0	69	81	180
Thermal conductivity [W/mK]	8	8	18	18
Electrical resistivity$\times 10^8$ [Ωm]	76	76	82	82

analysis was performed, thermal capacity and density of NiTi wire has to be included into material model. Both material properties were considered as constant in all investigated thermal conditions. Thermal capacity of NiTi wire has value 460 J/kgK 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. 2. 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/mK to 2 W/mK. Other thermal and electrical material parameters of screws for mechanical connection were compatible with material properties of teflon.

Table 2: Electrical and thermal material parametrs of clamp and connections

Component	Material	Thermal conductivity [W/mK]	Electrical resitivity [Ωm]	Thermal capacity [J/kgK]	Density [kg/m^3]
Clamp	copper	385	1.67×10^{-8}	396	8900
Mechanical connection		0.5/1/2	1×10^{12}	1000	2100
Electrical connection	copper	385	1.67×10^{-8}	396	8900

In the inner space of clamp, there was considered air with constant thermal properties – thermal conductivity 0.02 W/mK, thermal capacity 700 J/kgK and density 1.2 kg/m^3.

2.2 FEM simulation

Electro-thermal steady-state and transient analysis of SMA actuator was performed by code ANSYS Multiphysics. 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 elctro-thermal capabilities were set up and 2D surface effect element for convection and radiation heat transfer SURF 152.
Boundary conditions were prescribed as follows:

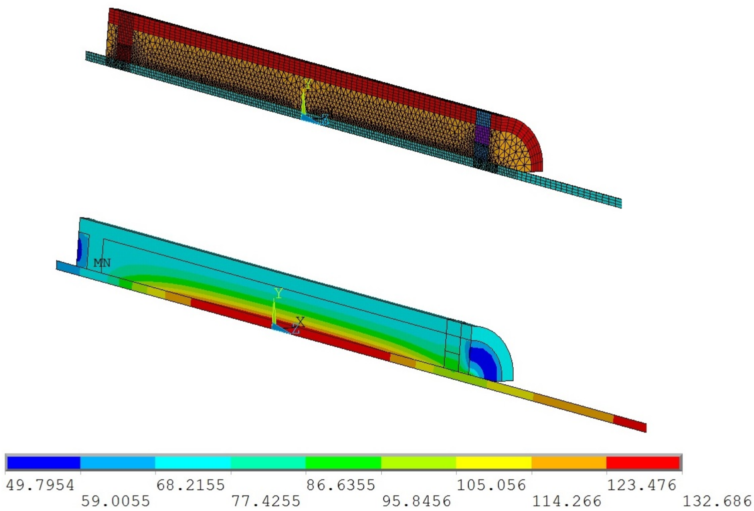

Figure 3: Top – mesh of SMA actuator, Bottom – temperature distribution near mechanical connection

- 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 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/mK or 1 W/mK, not all points of NiTi wire reach starting transformation temperatures. If we consider that thermal conductivity of mechanical connection is 2 W/mK, 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/mK 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 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)

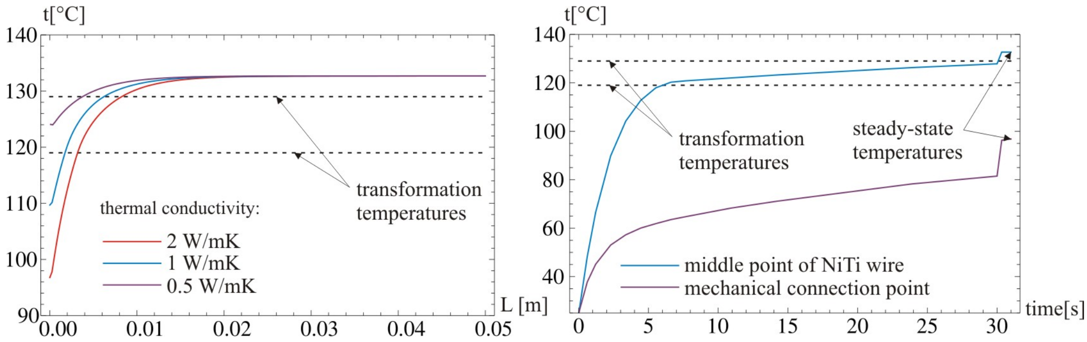

Figure 4: Left – Longitudinal distributions of temperature in active part of NiTi wire for all three thermal conductivities of mechanical connection, Right – thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 2 W/mK

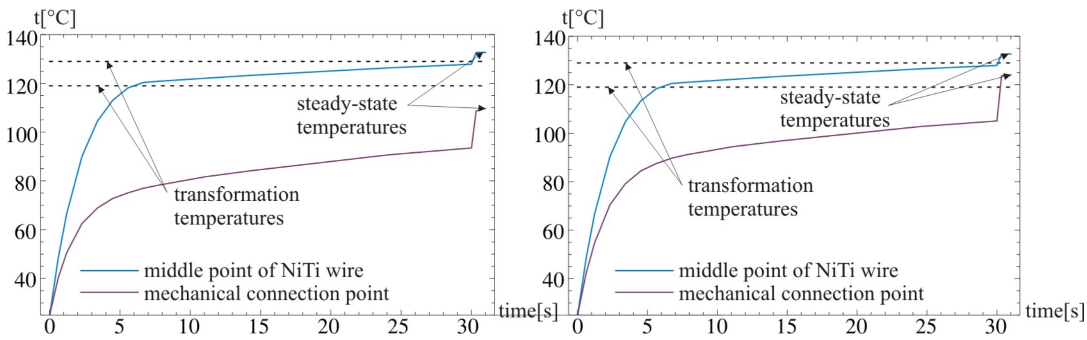

Figure 5: Left – thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 1 W/mK, Right – thermal dynamics of NiTi wire with thermal conductivity of mechanical connection 0.5 W/mK

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.

3 STRUCTURAL ANALYSIS

The goal of static structural analysis is to calculate actuation deformation of SMA thermal actuator, that is caused by phase change induced by increasing temperature. As was mentioned in chapter 2, only material, whose temperature cross transformation temperature transforms its phase and only this part of actuator works effectively. All three longitudinal temperature distributions in NiTi wire, which are shown in Fig. 4 Left, are considered.

3.1 Material parameters

In FEM code ANSYS, Souza-Auricchio material model of shape memory alloy with shape memory effect is implemented [4]. The model contains six parameters, which has

to be determined by experiment.
Our SMA wire can be described by following material parameters: Young modulus of austenite phase 45×10^9 Pa, Poisson ratio 0.3, hardening parameter 1000×10^6 Pa, temperature below which no twinned martensite is observed 343 K, elastic limit 110×10^6 Pa, material parameter β 4.49×10^6 Pa/K and maximal transformation strain 0.06.

3.2 FEM simulation

Static structural analysis of SMA actuator was performed by FEM code ANSYS Multiphysics. Because only NiTi wire is analyzed, 1D beam element BEAM 188, that supports SMA model with shape memory effect, was used. Only half of NiTi wire geometry was modeled (NiTi wire between middle and mechanical connection point). Left end of beam model, which represents mechanical connection of NiTi wire, was supported. At the right end of beam model there was prescribed force 14.1372 N, which causes tension stress in NiTi wire with value 200 MPa.

In order to simulate actuation deformation of SMA actuator, each simulation has to contain two loading states. In the first state, NiTi wire is loaded by structural force. The temperature considered in the first loading state is equal surrounding temperature. In the second state, temperature distribution, that was calculated in 3D electro-thermal analysis, is included into the model as thermal loading. This temperature distribution causes phase change in the NiTi wire locations, where temperature cross transformation temperature. The result of the phase change is the actuation deformation of SMA wire.

The longitudinal displacement of SMA actuator middle point caused by external force after the first loading state has value 2.4 mm. The middle point longitudinal actuation displacements of SMA wire after the second loading state for different temperature distributions are shown in Tab. 3.

Table 3: Dependence of SMA middle point actuation displacement on temperature distribution

Temperature distribution for mechanical connection with:	Actuation displacement of SMA middle point [mm]
thermal conductivity 0.5 W/mK	2.1
thermal conductivity 1 W/mK	1.9
thermal conductivity 2 W/mK	1.8

Fig. 6 Left and Right shows stress-strain relations for middle point and mechanical connection point with thermal conductivity of mechanical connection 0.5 W/mK, respectively. As we can see from this figure, actuation deformation of mechanical connection point is smaller than middle point deformation. This smaller deformation is caused by the fact, that the temperature of mechanical connection point does not cross finish phase change transformation temperature – this point has temperature only 124 °C and only

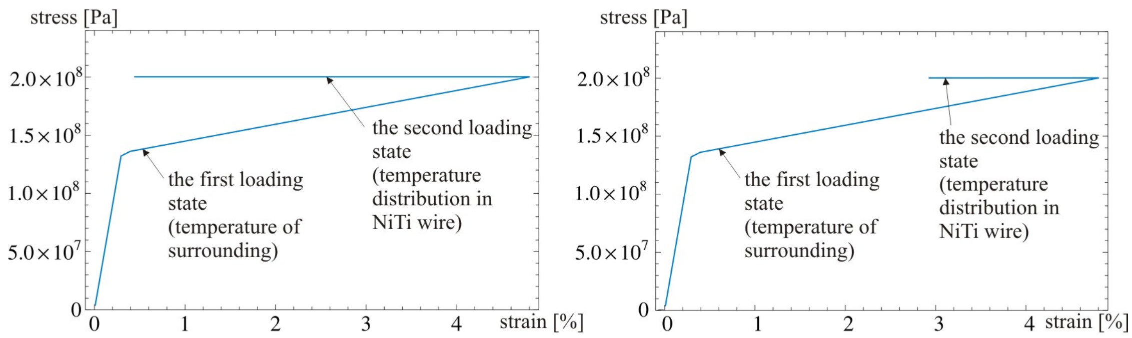

Figure 6: Stress-strain relations for following NiTi wire points: Left – middle point, Right – mechanical connection point, thermal conductivity of mechanical connection is 0.5 W/mK

adequate part of material is transformed from martensite phase to austenite phase.

4 CONCLUSIONS

Coupled electro-thermo-structural analysis of thermal SMA wire actuator made of Nickel-Titanium alloy was presented in the paper. The primary 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. The secondary goal of the paper was focused on structural analysis of NiTi wire and on the investigation of influence of temperature distribution on actuation deformation of SMA actuator. Our next research will be focused on shape optimization of mechanical connection of NiTi wire.

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