Evaluation of mechanical behavior of NiTi/NiTiCu bi-layer composites aided by analytical modelling and FEM validation

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Abstract

In this paper, NiTi/NiTiCu bi-layer composite as a novel material which shows pseudo-elastic and shape memory properties simultaneously, is made by diffusion bonding method. The interface of bonding was investigated by SEM and chemical composition gradient in the interface zone analyzed using line scan analysis with energy dispersive X-ray spectroscopy. An analytical model and FEM study is employed in order to investigating the tensile behavior of composites during loading and subsequent unloading. The bi-layer samples show two-way shape memory behavior after unloading without any complicated heat treatment and training process which is due to the stress sources generates at the interface of the bonding. Considering the results of the analytical modeling, the numerical simulations and the experiments, it is evident that the bi-layer composites with different thickness ratios provide adjustable mechanical behavior that can be considered in different SMA structural design.

Keywords: Shape memory alloys; Bi-layer composite; Two-way shape memory; Analytical modelling; FEM study.

1. Introduction

Shape memory alloys (SMA's) with two characteristics known as pseudo-elasticity and shape memory effect, have an special place in a vast range of applications (Bellouard, 2008, Lagoudas, 2008). Great potential of SMA's to enhance civil engineering structures, introduces them as a suitable candidate in various civil applications such as use in damping elements, self-rehabilitation structures and reinforced concretes (Janke et al., 2005, Song et al., 2006). Superior properties observed in SMA laminated composites as well as SMA reinforced composites, confirmed that they can be a new class of structural materials and can be an appropriate alternative for many structural materials (Pinto and Meo, 2015, Ali, 2016, Wang et al., 2017). Also SMA's showed extraordinary characteristic in seismic protection uses due to their fatigue resistance, superelasticity and stability of properties (Saadat et al., 2002, Dolce and Cardone, 2001a, Dolce and Cardone, 2001b).

SMA's have low controllability in both thermally- and stress-induced transformations, thus, controlling the deformation parameters, such as the plateau stress, the transformation and the pseudo-elastic strain, can be an interesting technique, to reach adjustable mechanical behavior in SMA components design (Lagoudas, 2008, Shaw and Kyriakides, 1997, Van Humbeeck, 1999).

Recently, using composite, multi-layered or functionally graded NiTi-based components produces different mechanical characteristics that can be useful in different applications (Wang et al., 2016, Mohri et al., 2016, Mohri et al., 2015b, Mohri and Nili-Ahmadabadi, 2015, Razali and Mahmud, 2015), e.g., a bi-layer NiTi thin film exhibited a combined pseudo-elastic behavior and shape memory effect, at the same time. Besides, the thermal hysteresis is reduced due to superior properties and an intrinsic two-way shape memory effect reported (Mohri et al., 2015a, Mohri and Nili-Ahmadabadi, 2015, Mohri et al., 2014, Mohri et al., 2015b, Mohri et al., 2016).

So far, many investigations have been conducted on the analytical modelling of functionally graded NiTi-based components as well as multilayer thin films (Ishida, 2015, Shariat et al., 2013a, Shariat et al., 2012, Shariat et al., 2013c, Shariat et al., 2013b, Shariat et al., 2014). Generally, the analytical models and FEM studies predict the global response of SMA components, under tensile loading and bending, also can reduce difficulties appear in experimental.

The aim of this research is to prepare NiTi/NiTiCu bi-layer composites with different thickness ratios using analytical modelling and FEM study. In addition it has been shown that the NiTi/NiTiCu bi-layer composite provide adjustable mechanical behavior that can be used in civil structures design, also it can be fabricated with a two-way shape memory effect without any complicated heat treatment and training process that can be considered in SMA components design.

2. Materials and Methods

Ni-rich (Ti-50.7at.%Ni as *A* layer) and Cu-included Ti-rich sheets (Ti-45at.%Ni-5at.%Cu as *M* layer) were prepared by alloying, using vacuum arc melting furnace followed by forging, solution annealing and also, hot and cold rolling, in order to reach the desirable thicknesses. Those sheets that are supposed to be used for the single layers, experience final 30 min anneal to improve the shape memory and superelastic characteristics. Samples annealing condition for each stage is shown in Table 1.

X-ray Diffraction (XRD) analysis of the bulk samples were performed to recognize the room temperature phases. For the bi-layer samples, the single layers were ground through 400, 800, 1200, 2000 and 4000 grit SiC papers and polished using a 40 nm colloidal Alumina suspension. Layers with 3:1 and 2:1 ratio (*M:A*) were bonded under diffusion bonding process in a vacuum tube furnace at 1000 ^{0}C, for 3h and under 20 MPa compressive stress applied by a super alloy fixture as schematically shown in Fig.1a. Afterwards, rolling followed by the annealing treatment, was conducted on the bonded layers to improve the shape memory and superelastic characteristics.

The interface of bonding was investigated using SEM, also Energy Dispersive X-ray spectroscopy were done using 30 analyze point in order to finding the chemical composition in the interface.

Tensile samples were prepared through the electric discharge machining. The gauge length of the single layer tensile samples was 30 mm and was 10 mm for the bi-layers. The single layer samples thickness was 0.9 mm and it was 0.6 mm for the bi-layer samples. Tensile behavior of the single-layers as well as the bi-layers were investigated employing loading-unloading test, with the strain rate of $2.8 \times 10^{-4}\ s^{-1}$. The nominal stress–strain curves of the single-layers and the bi-layers for tensile behavior are measured.

In order to obtain the stress-strain curve of the bi-layers with different thickness ratio analytical investigation conducted base on analytical modelling principles presented before (Taghizadeh; et al., 2017). FEM studies were conducted using the constitutive model developed by Lagoudas et al (Lagoudas et al., 2003), through a user-defined subroutine UMAT, in conjunction with constitutive behavior definition in ABAQUS for simulating the stress-strain diagrams. The material parameters required by the analytical model are σ_M and σ_A as the forward and the reverse transformation stresses, and ε_M and ε_A stand for the forward and the reverse transformation strains, respectively. The apparent elastic moduli of the austenite is denoted by E_A and also σ_{DT} and ε_{DT} are the de-twining stress and strain in tension, respectively. ε_{DTU} denotes the difference between the de-twinning strain in loading and unloading at the plateau stress level. σ_s and σ_f are the de-twining start and finish stress, and ε_{DC} denotes the de-twining strain in compression as schematically shown in Fig.1b. Also six different modulus of elasticity considered for the martensite phase, denoted by E_{M1} to E_{M6} for loading and unloading in tension for both

layers and loading in compression for the martensitic layer, respectively, as tabulated in Table 2. The material parameters required by the SMA_UM subroutine are Young's moduli of both austenite and martensite (E_A and E_M), the martensite start and finish and the austenite start and finish temperatures (M_s, M_f, A_s, and A_f, respectively), the maximum transformation strain (H), and the austenite and martensite stress influence coefficients ($\rho\Delta s^A$and $\rho\Delta s^M$, respectively) as tabulated in Table 3. The methods for extracting materials parameter for analytical model described in detail in previous work (Taghizadeh; et al., 2017) and also for FEM study by Lagoudas et al (Lagoudas et al., 2003).
Introducing the parameters defined in Table 1 into the set of stress–strain formulations derived in analytical model (Taghizadeh; et al., 2017), the stress–strain response of the NiTi/NiTiCu bi-layer composite is analytically predicted for different thickness ratios. Also the NiTi/NiTiCu bi-layer composites with different thickness ratios were designed and numerically analyzed in ABAQUS software using Lagoudas constitutive model with material parameters shown in Table 3 in order to obtaining stress-strain curves.

(a) (b)

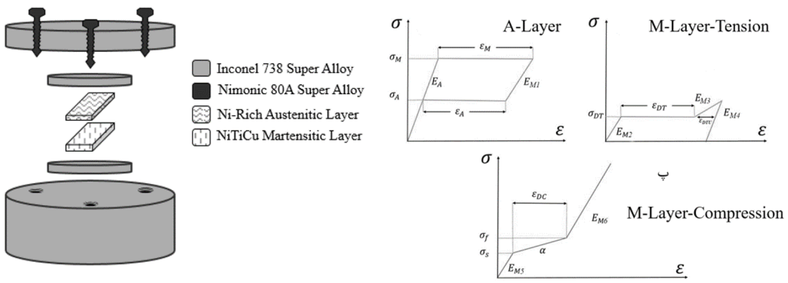

Fig.1. (a) Exploded view drawing for super alloy fixture used in sample construction stage and (b) A schematic for extracting material parameters.

Table 1. Samples annealing conditions used for each stage

Stage name	Time (min)	Temperature ℃
Solution Anneal	1440	1000
Rolling Inter-pass Anneal	15	750
Final Anneal	30	500

Table 2. Material properties of the NiTi/NiTiCu bi-layer composite used in analytical investigation

σ_M (MPa)	σ_A (MPa)	ε_M	ε_A	ε_{DT}	ε_{DC}	ε_{DTU}	σ_s (MPa)	σ_f (MPa)
380	100	0.053	0.040	0.030	0.028	0.015	100	240
E_A (GPa)	E_{M1} (GPa)	E_{M2} (GPa)	E_{M3} (GPa)	E_{M4} (GPa)	E_{M5} (GPa)	E_{M6} (GPa)	α (GPa)	σ_{DT} (MPa)
45	25	9.5	9.5	25	20	20	5	80

Table 3. Lagoudas constitutive model parameters used in the FEM analysis for the NiTi/NiTiCu bi-layer composite

Properties	E_A (GPa)	E_M (GPa)	H	$\rho\Delta s^M$	$\rho\Delta s^A$	M_s (K)	M_f (K)	A_s (K)	A_f (K)
A layer	45	25	0.045	-36432	-116059	175	133	192	223
M layer	45	15	0.048	-1577146	-1373077	330	316	334	347

3. Results and Discussion

Fig. 2a shows the X-ray patterns of the single layers. The solid line related to the austenitic sample, illustrates only the austenite peak, where the diffraction pattern of the martensitic sample (The dashed line) shows the martensite phase peaks. In other word, the A and the M layer samples contain fully austenite and fully martensite phases in ambient temperature, respectively as reported by the literature (Iijima et al., 2008, Riva et al., 1995).

Fig. 2b illustrates the bi-layer SEM images after annealing with line scan composition data obtained from Energy Dispersive X-ray spectroscopy. This SEM image shows three different layer in cross section of the bilayer composite; Ni-rich, interface, NiTiCu layer. The left and right dashed lines indicate the bonding interface and the phase interface after diffusion bonding process, respectively. As seen in Fig. 2b, line scan curves indicates composition gradients at the interface of the bonding. The experimental observations and theoretical calculations (Mohri et al., 2014), obtained from the analysis of line scan and the diffusion equation under above annealing condition, confirmed that the diffusion depths for Ni and Cu were about 30 and 15 μm, respectively. Although the interface of bonding could affect the mechanical behavior of the NiTi/NiTiCu bi-layers, considering the total thickness of composite, the fraction of concentration gradient area under above annealing condition is negligible (~0.05), so it is assumed that the *A* and the *M* layer maintain their full pseudo-elastic and full de-twinning properties after the diffusion bonding.

Fig. 3 shows the stress–strain diagram of the single layers as well as the bi-layers under uniaxial tensile loading. As shown in Fig. 3, considering the stress plateaus for both the *A* and the *M* layer, the stress plateau for the NiTi/NiTiCu bi-layer composites lie between those ones for the single layers. Also increasing the *A* to *M* thickness ratio, increases the stress plateau and the pseudo-elastic strain to the higher levels.

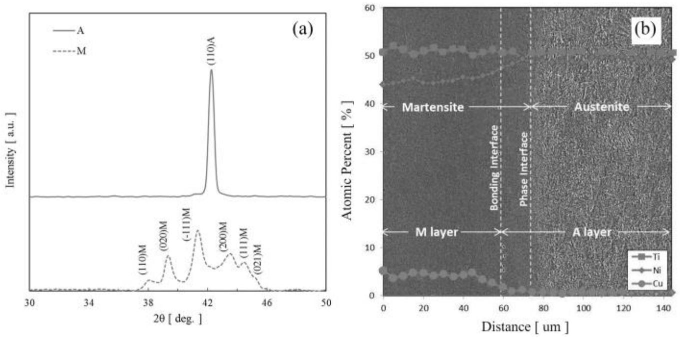

Fig. 2. XRD patterns for the A and the M layer of the NiTi alloy (a), and SEM image of the bi-layer cross section (b).

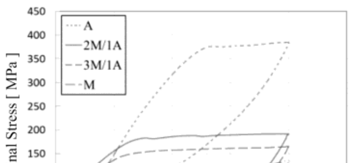

Fig. 3. Nominal stress-strain curves for single layers and the bi-layers.

Fig. 4 illustrates stress-strain curves for NiTi/NiTiCu bi-layer composites obtained from analytical modeling base on material parameters shown in Table 1. In Fig. 4a stress-strain curves for Ni-rich (*A* layer), Ti-rich (*M* layer) and a 2:1 (*M*:*A*) bi-layer is shown. Similar to Fig. 3. As shown in Fig. 4a the stress plateau for bi-layer lies between the stress plateaus for both single layers. Also the transformation strain of the bi-layer is more than the transformation strain of the Ti-rich layer and it's less than that one for Ni-rich layer.

To have more investigation on the effects of the thickness ration in bi-layer samples, analytical results for thickness ratio changing is shown in Fig. 4b. As shown in Fig. 4b, bi-layer composites deformation parameters can be adjusted with varying the thickness ratios, e.g., for 1:2 (*M*:*A*) thickness ratio the stress plateau for the composite is 280 MPa while it is 150 MPa for 3:1(*M*:*A*). For overall comparison, the results of the experimental tests, FEM studies and analytical model are shown in Fig. 5. It is seen that the analytical model predictions are in a good agreement with the experimental observations as well as the FEM studies.

Fig. 6 shows the effects of changing *A*/*M* ratio on the plateau stress and strain of the NiTi/NiTiCu bi-layer composites obtained from the analytical and FEM methods. In order to validating the results of the analytical modeling and simulations, the experimental results of the plateau stress and strain of composites with two thickness ratios are presented in Fig. 6. Considering the results of the analytical modelling, FEM study and experimental tests, it is evident that the bi-layer composites with different thickness ratios show different deformation parameters and varying the relative thickness of the layers leads to more handling condition that can be considered in designing SMA components.

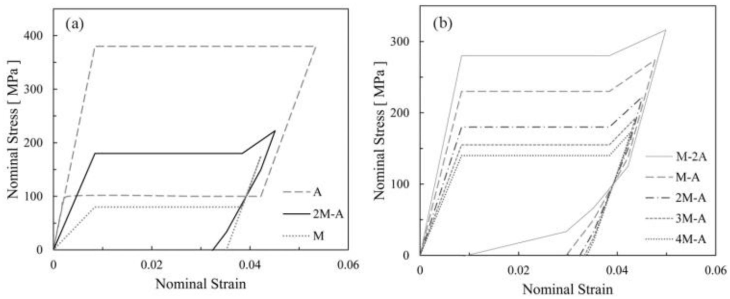

Fig. 4. Nominal stress-strain curves for NiTi/NiTiCu bi-layers; (a) Compared to the single layers (b) The effects of thickness ratio

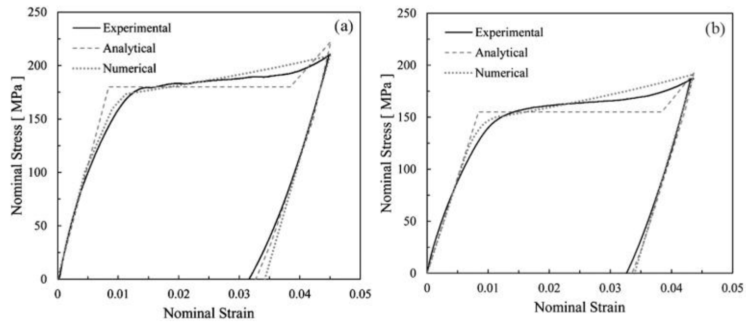

Fig. 5. The nominal stress–strain curves of the NiTi/NiTiCu bi-layer composites under uniaxial tensile loading: (a) 2:1 ratio (*M:A*); (b) 3:1 ratio (*M:A*).

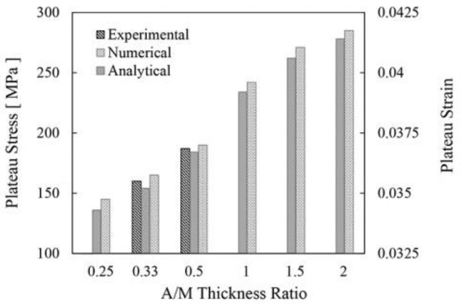

Fig. 6. The effects of changing the thickness ratio on the plateau stress and strain of the NiTi/NiTiCu bi-layer composite.

Fig. 7 shows the bi-layer composites with 3:1 (*M*:*A*) thickness ratios experienced 4 to 18% strain after unloading and subsequent heating. Because of stress source existing, after unloading the composites provide a bent toward the Ni-rich side. This stress source originates at the interface of bonding due to different unloading behavior and remaining stress which is stored to the austenitic layer (Shariat et al., 2013a). Due to the single layers stress-strain curves which is shown in Fig. 3, martensitic single layer shows permanent strain during unloading which is recovered by heating while austenitic single layer fully recovers during unloading. This different unloading behavior leads to stress source existing in bi-layer samples which is releases after removing the samples from the tensile device clamps and provide a bent toward the austenitic side. As shown in Fig. 7, after heating the curved samples, the remaining strain in martensitic layer recovers due to the shape memory effect and cause the bi-layer return to the initial shape (one-way shape memory effect).

It was observed that increasing the loading strain (up to 12 %) due to the significant plastic strain generation in martensitic layer, cause the bi-layer to bent after cooling to room temperature and leads to two-way shape memory behavior as seen in Fig. 7, therefore the bi-layer composite provide high potential to show two-way shape memory behavior after a simple loading-unloading cycle without any complicated heat treatment and training process, also these properties are maintained for 1000 loading-unloading cycles which can be considered in designing SMA components with two-way shape memory effect, e.g., actuators with reciprocating movement.

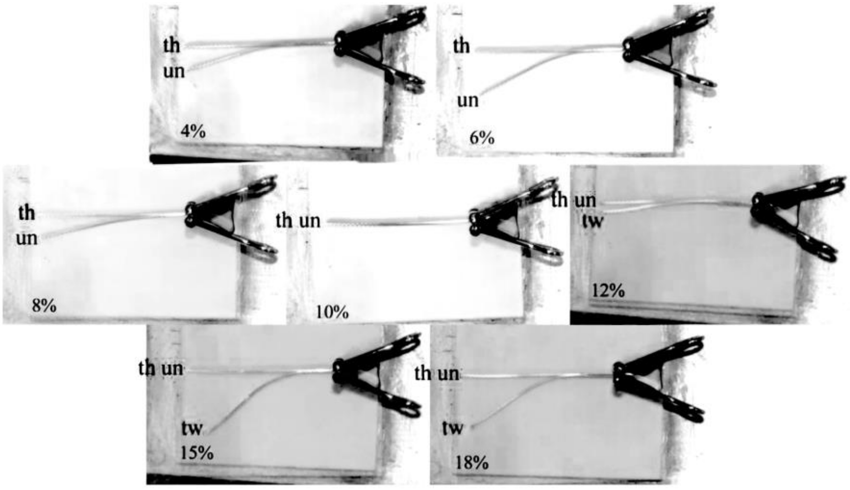

Fig. 7. Effects on loading-unloading (un) and subsequent heating (th) on curvature of the bi-layers experienced 4-18 % strains.

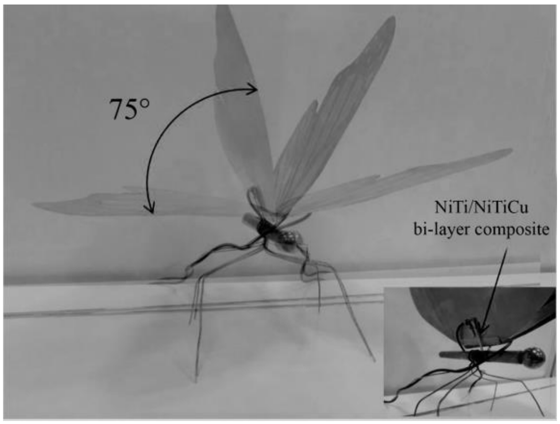

Fig. 8. Butterfly structure equipped with NiTi/NiTiCu bi-layer composites.

In order to showing the ability of NiTi/NiTiCu bi-layer composite, a butterfly shaped structure was designed with a bi-layer composite with 3:1 (*M*:*A*) thickness ratio. As seen in Fig. 8, when the bi-layer samples, which are located under the wings of the butterfly structure, heated by electric current, recovers their straight initial shapes and causes the wings to move upward. As the electrical current is interrupted, the temperature decreases, and the Ti-rich layer experience the martensitic phase transformation cause the bi-layer provide a bent and the wings move downward subsequently.

4. Conclusions

(1) NiTi/NiTiCu bi-layer composites consisting of austenitic and martensitic layers with different thickness ratio are produced by the diffusion annealing process. SEM image and line scan analyze are used to study the interface of the bonding. The bi-layer composites show adjustable deformation behavior and varying the relative thickness of the layers, results in varying deformation parameters.

(2) An analytical model is used to describe the deformation behavior of the NiTi/NiTiCu bi-layer composites during uniaxial tensile loading-unloading and the closed-form equations are derived for the nominal stress–strain variations. FEM studies are conducted using Lagoudas 3D constitutive model implemented in a user-subroutine UMAT in conjunction with constitutive behavior definition in ABAQUS, for simulating the stress-strain diagrams. The results shows a good agreement with the experimental.

(3) Increasing the *A*/*M* thickness ratio in the NiTi/NiTiCu bi-layer composites increases the stress plateau and the pseudo-elastic strain to higher levels and results in increasing the transformation strain. Therefore, the NiTi/NiTiCu bi-layer composites with different thickness ratios provide adjustable mechanical behaviors that can be used in design of SMA structures.

(4) The bi-layer composite provide high potential to show two-way shape memory behavior after a simple loading-unloading cycle without any complicated heat treatment and training process which can be considered in designing SMA components with two-way shape memory effect.

References

ALI, A. 2016. Interfacial strength and dynamic behaviour modelling of a SMA based laminated hybrid composite.

BELLOUARD, Y. 2008. Shape memory alloys for microsystems: A review from a material research perspective. *Materials Science and Engineering: A,* 481, 582-589.

DOLCE, M. & CARDONE, D. 2001a. Mechanical behaviour of shape memory alloys for seismic applications 1. Martensite and austenite NiTi bars subjected to torsion. *International Journal of Mechanical Sciences,* 43, 2631-2656.

DOLCE, M. & CARDONE, D. 2001b. Mechanical behaviour of shape memory alloys for seismic applications 2. Austenite NiTi wires subjected to tension. *International Journal of Mechanical Sciences,* 43, 2657-2677.

IIJIMA, M., BRANTLEY, W., GUO, W., CLARK, W., YUASA, T. & MIZOGUCHI, I. 2008. X-ray diffraction study of low-temperature phase transformations in nickel–titanium orthodontic wires. *dental materials,* 24, 1454-1460.

ISHIDA, A. 2015. Ti–Ni–Cu/polyimide composite-film actuator and simulation tool. *Sensors and Actuators A: Physical,* 222, 228-236.

JANKE, L., CZADERSKI, C., MOTAVALLI, M. & RUTH, J. 2005. Applications of shape memory alloys in civil engineering structures—overview, limits and new ideas. *Materials and Structures,* 38, 578-592.

LAGOUDAS, D., BO, Z., QIDWAI, M. & ENTCHEV, P. 2003. SMA UM: user material subroutine for thermomechanical constitutive model of shape memory alloys. *Texas A&M University College Station TX*.

LAGOUDAS, D. C. 2008. *Shape memory alloys: modeling and engineering applications,* Springer Science & Business Media.

MOHRI, M. & NILI-AHMADABADI, M. 2015. Phase transformation and structure of functionally graded Ni–Ti bi-layer thin films with two-way shape memory effect. *Sensors and Actuators A: Physical,* 228, 151-158.

MOHRI, M., NILI-AHMADABADI, M. & FLEGE, S. 2014. Diffusion evaluation of Cu in NiTi Bi-layer thin film interface. *Journal of Alloys and Compounds*, 594, 87-92.

MOHRI, M., NILI-AHMADABADI, M., IVANISENKO, J., SCHWAIGER, R., HAHN, H. & CHAKRAVADHANULA, V. S. K. 2015a. Microstructure and mechanical behavior of a shape memory Ni–Ti bi-layer thin film. *Thin Solid Films,* 583, 245-254.

MOHRI, M., NILI-AHMADABADI, M., POURYAZDANPANAH, M. & HAHN, H. 2016. Evaluation of structure and mechanical properties of Ni-rich NiTi/Kapton composite film. *Materials Science and Engineering: A,* 668, 13-19.

MOHRI, M., NILI-AHMADABADI, M. & IVANISENKO, J. 2015b. On the Super-Elastic and Phase Transformation of a Novel Ni-Rich/NiTiCu Bi-Layer Thin Film. *Advanced Engineering Materials,* 17, 856-865.

PINTO, F. & MEO, M. 2015. Mechanical response of shape memory alloy–based hybrid composite subjected to low-velocity impacts. *Journal of Composite Materials,* 49, 2713-2722.

RAZALI, M. F. & MAHMUD, A. S. 2015. Gradient deformation behavior of NiTi alloy by ageing treatment. *Journal of Alloys and Compounds,* 618, 182-186.

RIVA, G., VANELLI, M. & AIROLDI, G. 1995. A new calibration method for the X-ray powder diffraction study of shape memory alloys. *physica status solidi (a),* 148, 363-372.

SAADAT, S., SALICHS, J., NOORI, M., HOU, Z., DAVOODI, H., BAR-ON, I., SUZUKI, Y. & MASUDA, A. 2002. An overview of vibration and seismic applications of NiTi shape memory alloy. *Smart materials and structures,* 11, 218.

SHARIAT, B., LIU, Y., MENG, Q. & RIO, G. 2013a. Analytical modelling of functionally graded NiTi shape memory alloy plates under tensile loading and recovery of deformation upon heating. *Acta Materialia,* 61, 3411-3421.

SHARIAT, B. S., LIU, Y. & RIO, G. 2012. Thermomechanical modelling of microstructurally graded shape memory alloys. *Journal of Alloys and Compounds,* 541, 407-414.

SHARIAT, B. S., LIU, Y. & RIO, G. 2013b. Mathematical modelling of pseudoelastic behaviour of tapered NiTi bars. *Journal of Alloys and Compounds*, 577, S76-S82.

SHARIAT, B. S., LIU, Y. & RIO, G. 2013c. Modelling and experimental investigation of geometrically graded NiTi shape memory alloys. *Smart Materials and Structures,* 22, 025030.

SHARIAT, B. S., LIU, Y. & RIO, G. 2014. Pseudoelastic behaviour of perforated NiTi shape memory plates under tension. *Intermetallics,* 50, 59-64.

SHAW, J. A. & KYRIAKIDES, S. 1997. On the nucleation and propagation of phase transformation fronts in a NiTi alloy. *Acta materialia,* 45, 683-700.

SONG, G., MA, N. & LI, H.-N. 2006. Applications of shape memory alloys in civil structures. *Engineering structures*, 28, 1266-1274.

TAGHIZADEH;, M., NILI-AHMADABADI;, M., BAGHANI;, M. & MALEKOSHOARAEI;, M. H. 2017. A combined analytic, numeric, and experimental investigation on NiTi/NiTiCu bi-layer composites under tensile loading. *Advanced Engineering Materials*.

VAN HUMBEECK, J. 1999. Non-medical applications of shape memory alloys. *Materials Science and Engineering: A,* 273, 134-148.

WANG, E., TIAN, Y., WANG, Z., JIAO, F., GUO, C. & JIANG, F. 2016. A study of shape memory alloy NiTi fiber/plate reinforced (SMAFR/SMAPR) Ti-Al laminated composites. *Journal of Alloys and Compounds*.

WANG, E., TIAN, Y., WANG, Z., JIAO, F., GUO, C. & JIANG, F. 2017. A study of shape memory alloy NiTi fiber/plate reinforced (SMAFR/SMAPR) Ti-Al laminated composites. *Journal of Alloys and Compounds,* 696, 1059-1066.