Residual stresses in shape memory alloy fiber reinforced aluminium matrix composite

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Abstract. Process-induced residual stress in shape memory alloy (SMA) fiber reinforced aluminum (Al) matrix composite was simulated by ANSYS APDL. The manufacturing process of the composite named as NiTi/Al is start with loading and unloading process of nickel titanium (NiTi) wire as SMA to generate a residual plastic strain. Then, this plastic deformed NiTi wire would be embedded into Al to become a composite. Lastly, the composite is heated form 289 K to 363 K and then cooled back to 300 K. Residual stress is generated in composite because of shape memory effect of NiTi and mismatch of thermal coefficient between NiTi wire and Al matrix of composite. ANSYS APDL has been used to simulate the distribution of residual stress and strain in this process. A sensitivity test has been done to determine the optimum number of nodes and elements used. Hence, the number of nodes and elements used are 15680 and 13680, respectively. Furthermore, the distribution of residual stress and strain of nickel fiber reinforced aluminium matrix composite (Ni/Al) and titanium fiber reinforced aluminium matrix composite (Ti/Al) under same simulation process also has been simulated by ANSYS APDL as comparison to NiTi/Al. The simulation results show that compressive residual stress is generated on Al matrix of Ni/Al, Ti/Al and NiTi/Al during heating and cooling process. Besides that, they also have similar trend of residual stress distribution but difference in term of value. For Ni/Al and Ti/Al, they are 0.4% difference on their maximum compressive residual stress at 363K. At same circumstance, NiTi/Al has higher residual stress value which is about 425% higher than Ni/Al and Ti/Al composite. This implies that shape memory effect of NiTi fiber reinforced in composite able to generated higher compressive residual stress in Al matrix, hence able to enhance tensile property of the composite.

1. Introduction
Shape memory alloys are a group of metallic alloys that can return to their original form in terms of shape and size after subjected to a memorization process between two transformation phases, which is temperature dependent and this transformation phenomenon is known as the shape memory effect [1].
The shape memory effect of shape memory alloy is used to design smart material. This type of smart material also known as SMA composite [2] and the design concept have been proposed by the Watanabe et. al [3], where the illustration of SMA composite design concept is show as Figure-1. The metal matrix composite fiber reinforced with SMA material will have better material characteristic and be safer because compressive stress is often seems as good stress for matrix composite because it can increase fatigue life of the component by reduce micro-crack of composite [2,4]. Therefore, knowledge and understanding of residual stress at matrix of SMA composite is very important because by knowing the distribution of residual stress at the design process would help the research to design better SMA composite and hence improve the performance of composite.

2. Methodology
This research is focus on simulation of three composite models. The composite models are NiTi/Al, Ni/Al and Ti/Al. The flow chart of the simulation and the geometry of the composite models is shown in Figure-2 and Figure-3, respectively. ANSYS APDL is used to simulate the residual stress of the composites. There are four types of material involves i.e. Al and three types of fiber, Ni, Ti and NiTi. The material property of them is shown as Table-1 and Table-2. The technique to determine the phase transformation temperatures in NiTi are briefly explained in Tan et al [5].

Quarter model is used in this simulation as shown in Figure-4. Quarter model is chosen because it can reduce great number of nodes and elements in finite element furthermore the model is symmetric to both loading and geometry condition. The boundary condition in this case is symmetric boundary condition and would get symmetric answer.

| Parameter              | Symbol | Al [6] | Ni [7] | Ti [8] | Unit          |
|------------------------|--------|--------|--------|--------|--------------|
| Young Modulus          | $E$    | 70     | 202.5  | 103    | GPa          |
| Poisson Ratio          | $\nu$  | 0.33   | 0.29   | 0.32   | -            |
| Thermal Expansion      | $\alpha$ | 23.5e-6 | 12.3e-6 | 8.6e-6 | K$^{-1}$ or $\sigma_{c}^{i}$ |
| Yield strength         | $\sigma_y$ | 160     | 185    | 155.5  | MPa          |
| Tensile strength       | $\sigma_s$ | 170     | 434    | 215.5  | MPa          |
Figure-2: Simulation flowchart

Figure-3: The model for simulation
Table-2: Nickel Titanium material property [9]

| Parameter                                      | Symbol | Value/Description | Unit  |
|------------------------------------------------|--------|-------------------|-------|
| A) Elastic model                               |        |                   |       |
| Young modulus at austenite phase              | E      | 70e3              | MPa   |
| Poisson ratio                                  | ν      | 0.3               | -     |
| B) SMA model                                   |        |                   |       |
| Maximum transformation strain                 | $\bar{\varepsilon}_L$ | 0.07              | MPa   |
| Hardening parameter                           | h      | 500               | MPa   |
| Temperature scaling factor                   | $\beta$ | 8.3               | MPa/K |
| Reference temperature                         | $M_s$  | 289               | K     |
| Hysteresis loop amplitude                     | R      | 120MPa            | K     |
| Lode dependency parameter                    | m      | 0                 | -     |
| Young modulus at martensite phase            | $E_m$  | 70e3              | MPa   |

Then, the quarter model would subject to loading step follow the design method present in Figure-1 and the simulation step that follow the steps of Figure-2 has been modified and is shown as flow diagram in Figure-5. In order to simplified the model, the NiTi wire is embedded in Al matrix using similar technique in Jamian et al. [10, 11]. After solve all the load step, the data of residual stress would be able to read and plot out. However, before to start the simulation, sensitivity test shall conduct to determine the optimum number of nodes and elements.

![Quarter model](image)

Figure-4: Quarter model

3. Results and Discussion
Before start doing simulation on NiTi/Al composite, modeling of NiTi wire has been done to determine the tensile loading required to generate maximum residual strain. The stress-strain relationship of NiTi is shown in Figure-6. Figure-6 indicated the maximum residual strain of NiTi wire is about 5.6 % and the maximum pressure required to generate this strain is about 190MPa.
Furthermore, as shown in Figure-6 the tensile loading required to induce phase transformation from multi variant oriented martensite to single variant oriented martensite is about 150 MPa. The residual strain of NiTi wire can be generated by subjected tensile loading 150MPa above but the residual strain is reach maximum when the tensile loading reached 190MPa. In this work, tensile loading 240MPa is chosen to generate maximum residual strain for NiTi wire before placed into Al matrix.

![Figure-5: Load step involved in simulation](image)

![Figure-6: Stress-strain graph of NiTi](image)

The maximum residual strain will be treated as maximum residual strain for simulation of NiTi model. Then, to determine the optimum number of elements a sensitivity test has been conducted. In sensitivity test, a testing node has been chosen to compare the result of stress in z-direction, $S_z$ with
difference value of elements and nodes. The result of sensitivity test has been shown as Table-3. The optimum number of element and node is 13680 and 15680, respectively. This number of number and nodes has been used to simulate in other two composite models.

| Element | Node | Stress in z-direction, Sz (MPa) | error |
|---------|------|--------------------------------|-------|
| 1890    | 2432 | 198.4                          | -     |
| 4455    | 5440 | 199.52                         | 1.12  |
| 8385    | 9856 | 199.87                         | 0.35  |
| 9675    | 11264| 199.91                         | 0.04  |
| 11520   | 13328| 199.96                         | 0.05  |
| 12960   | 14896| 199.99                         | 0.03  |
| 13680   | 15680| 199.99                         | 0      |

The residual stress distribution of NiTi/Al composite generated during manufacturing process has been simulated by ANSYS APDL. There are total 7 load steps involved in the simulation process and the time interval for each load step is 1s. Therefore, the total time taken of the simulation process is 7s. The time taken for each load step is set like this because the variable of the model is time invariant and easier to analyze during discussion. The result of stress in z-direction, Sz distribution for every 1s or load step is shown as Figure-7. The stress from origin to 1.802mm away in x-direction is showed in all graphs. Furthermore, the contour plot of each load steps has been shown in Figure-7(a) to (g) for the better inspection on the residual stress distribution.

Figure-7(a) indicates the stress distribution of NiTi/Al composite at time=1s. The tensile load applied on the NiTi wire is 120MPa which is the half of the tensile loading. Based on Figure-7(a), the stress is constant between range of 0mm to 0.36mm. The stress value is 120MPa which is equal to the tensile load applied on the NiTi wire. The stress value is decline slowly after 0.36mm and become zero around 0.78mm because there is modified Al matrix constraints the deformation of NiTi wire.

Figure-7(b) indicates the stress increased from 120MPa to 240MPa between range of 0mm to 0.36mm at time=2s. This stress value is same as the tensile loading applied on NiTi wire. The stress value is declined after 0.36mm and reach zero at 0.78mm.

After loading process is completed, unloading process is started at load step 3 and the residual stress distribution at time=3s is shown as Figure-7(c). By inspected on Figure-7(c), the residual stress is significantly small and can be treated as stress free after unloading. The stress is no exactly zero because numerical method is used to obtain the value while running the solver.

Initially, the NiTi wire is pulled alone without presence of Al matrix because ANSYS APDL is unable to add Al matrix element to the NiTi wire after run the solver. Therefore, the complete model of NiTi/Al composite is built first although the Al is does not exist at the beginning of the simulation process. Then, the Al element are deactivated at load step 4 and run the first three load step again to eliminate load effect of Al elements on the NiTi wire. After deactivation of Al matrix, the stress distribution is change but still significant small because the Al and NiTi wire is suppose in stress free condition as shown in Figure-7(d).
Figure-7: Stress in z-direction, Sz distribution of NiTi/Al composite at different time step (in MPa). (a) step 1, (b) step 2, (c) step 3, (d) step 4, (e) step 5, (f) step 6 and (g) step 7.
Then, the model undergo load step 5 to activate the Al matrix elements surrounding of NiTi wire. The Al matrix is modified to low Young modulus material to reduce simulation failure in load step 4. Hence, in this step Al matrix have converted back to original material property after activated the element. The stress distribution as shown in Figure-7(e) is same as load step 4 since no external load is applied on composite. Then, the simulation is proceeded to load step 6 where the temperature of the model increased from 289K to 363K. The residual stress is generated in this load step where there are no external force acting on it.

Figure-7(f) shows the residual stress distribution of NiTi/Al composite at time=6s. The residual stress generated in this load step is due to shape memory effect and mismatch of thermal expansion between Al matrix and NiTi fiber reinforcement. Based on Figure-7(f), the residual stress is around 520 MPa at origin and increased to 585 MPa at 0.36mm which is in the region of NiTi wire. Then, the residual stress starts to decrease drastically from 585MPa to a maximum compressive residual stress value -70 MPa around 0.78mm which is at region on Al matrix. The shrinkage of NiTi is due to shape memory effect and expansion of Al matrix due to increase of thermal load. This phenomenon has caused the residual stress is decreased along the interfacial between matrix and fiber due to the pulling action of NiTi on Al matrix. This pulling action generated a compressive residual stress on Al matrix that surrounded the NiTi wire. However, the compressive residual stress is slowly decrease for the region far away from the NiTi wire and eventually reach a saturated value -5.324 MPa.

Then, for load step 7 the model temperature is decreased from 363K to 300K (room temperature). Based on Figure-7(g), the residual stress distribution pattern is still the same but the residual stress value is decreased if compare with Figure-7(g). The maximum residual stress is about 210.8 MPa which is decreased about 64% and the minimum residual stress is about -2MPa which is decreased about 62%.

Beside simulation stress distribution of NiTi/Al composite is simulated, stress distribution of Ni/Al composite and Ti/Al composite also has been simulated. Then, the maximum compressive stress generated in Al matrix in Ni/Al and Ti/Al composite then would be compared with NiTi/Al composite at 363K and 300K.

| Temperature | NiTi/Al | Ni/Al  | Ti/Al  |
|-------------|---------|--------|--------|
| 363 K       | -70.964 MPa | -13.483 MPa | -13.537 MPa |
| 300 K       | -30.732 MPa  | -2.004 MPa   | -2.012 MPa   |

Table-4 indicates the NiTi/Al has highest compressive residual stress compared to Ni/Al and Ti/Al. The compressive residual stress of NiTi/Al generated during heating process about 425 % higher than Ni/Al and Ti/Al. This is because the residual stress of NiTi/Al is generated with combination shape memory effect of NiTi and mismatch of thermal expansion of between matrix and fiber. In contrast, Ni/Al and Ti/Al do not have shape memory effect during heating process so they formed weaker compressive residual stress compared with NiTi/Al. Furthermore, the compressive residual stress of these composites is higher at higher temperature. This is because of the degree of thermal expansion of Al matrix is higher when the temperature of composite is higher.

4. Conclusion
The process induced residual stress of NiTi/Al has been simulated by ANSYS APDL version 16.2. Furthermore, two others composite, Ni/Al and Ti/Al, also has been simulated.

After simulation, the three types of composites able to generate compressive residual stress on Al matrix. Compressive residual stress on Al matrix able to enhance the material property of composite by closed the micro crack of the Al matrix of the composite. However, after compared the maximum residual stress generated by difference composites. The NiTi/Al, SMA composite, is the superior
because it has about 425% of compressive residual stress value higher than Ni/AL and Ti/Al. The higher value of compressive residual stress is caused by the residual stress of NiTi/Al is induced with combination of shape memory effect and mismatch of thermal expansion of matrix and fiber. Meanwhile, the residual stress of Ni/Al and Ti/Al is only induced by the mismatch of thermal expansion.

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