Advanced Shape Memory Alloy Material Models for ANSYS

Kaan Divringi & Can Ozcan

Ozen Engineering Inc 1210 E Arques Ave Suites 206/207 Sunnyvale, CA 94085 (408) 732-4665 www.ozeninc.com info@ozeninc.com

Introduction

Shape Memory Alloy (SMA) materials such as Nitinol have found a variety of applications in recent years due to its unique behavior under mechanical and thermal loads. The shape memory effect for which it is named is the ability of the material to undergo thermally recoverable deformation on the order of 6% or more strain. In the shape memory phase below a certain temperature, Nitinol will present stiffness similar to soft copper wire, allowing easy deformation into desired shapes. As Figure 1 shows, upon the application of heat to bring the material above a certain transition temperature, the material returns to its original shape, undoing the previous deformation.

Although the shape memory effect is unusual and useful, in many applications it is not exploited due to the similarly unusual and useful pseudoelastic phase. When the temperature of Nitinol is above the transition temperature, it can undergo large elastic deformations, approaching 8-10% in many cases, while presenting stiffness greater than similarly flexible materials. The hysteresis loading path that it exhibits over the range of deformation is useful as well for its so called 'biased stiffness' characteristic, shown on Figure 2. If the loading is stopped along this hysteresis effect, the material will seem to present two different elastic moduli: very stiff to compressive loading and very flexible to tensile loads. This characteristic can be used in a stent, for example, to apply gentle constant pressure into the vessel it is expanding against, yet stiffly resist pressure from the vessel on the stent to close (Duerig, 2000).

The source of the unique behavior of SMA materials is the multiphase crystalline structure. The phases of Nitinol correspond to configurations of Nickel and Titanium in the crystal structure. The austenite phase is a cubic configuration of the crystal lattice, structurally stiff and occurring at higher temperatures. The martensite phase is a phase found at lower temperatures and is not as stiff as austenite. As shown in Figure 3, the martensite usually begins in a twinned configuration and upon loading becomes detwinned, retaining the strain experienced in this phase. Increasing the temperature sufficiently will induce phase change to austenite, returning the material to the original shape. While the material is pseudoelastic, the austenitic phase occurs at when there is no loading and deformation is not retained. The hysteresis loading path in is due to the initiation and completion of the phase transitions from martensite and austenite due to stress loading. While the latter is common to simulate in existing



Figure 1 - Shape memory alloy deformation and temperature induced recovery



Figure 2 - Pseudoelastic Nitinol phase demonstrating full loading path (solid) as well as partial loading paths (dashed)



Figure 3 - Flowchart illustrating the phases of Nitinol and their process relations

shape memory alloy materials, the former shape memory effect that is not found in most material models. In the following pages, a material model with all of the characteristics described above will be demonstrated.

Implemented Material Model

The following material model was implemented in the ANSYS 12.1 Finite Element Analysis (FEA) software as a User Programmable Feature (UPF). The material model was written in Fortran code, compiled against the Intel Fortran compiler v10.1 and linked into a custom ANSYS executable via Microsoft Visual Studio 2005 Professional.

The material model is an implementation of a previously developed unified constitutive model (Lagoudas, 1996). Details of the constitutive model can be found in the referenced paper and the focus of the present work will be to describe its implementation into ANSYS.



Material Parameters of Material Model

Figure 4 - Material parameters for the SMA model, showing the relation between the stress-strain and the temperaturephase diagram



As shown in the Table 1, the thermomechanical behavior of the SMA model can be specified by 12 constants, 9 of which are shown Figure 4. These parameters can be determined from a unixial test in the pseudoelastic phase as well as a stress-temperature diagram. The stress influence coefficients can be determined from the following relations:

$$\rho \Delta s^{A} = -\frac{\sigma^{A}}{T_{test} - A^{Os}} H$$
$$\rho \Delta s^{M} = -\frac{\sigma^{M}}{T_{test} - M^{Os}} H$$

Material Parameter	Value
Elastic stiffness of austenite E ^A	70 GPa
Elastic stiffness of martensite E ^M	30 GPa
Poisson's ratio v	0.33
Coefficient of thermal expansion for austenite α^A	22 x 10 ⁻⁶ K ⁻¹
Coefficient of thermal expansion for martensite α^{M}	22 x 10 ⁻⁶ K ⁻¹
Martensitic start temperature M ^{0s}	291 К
Martensitic finish temperature M ^{0f}	271 K
Austenitic start temperature A ^{0s}	295 К
Austenitic finish temperature A ^{0f}	315 K
Maximum transformation strain H	0.05
Stress influence coefficient for austenite $\rho \Delta s^A$	-0.35 MPa K ⁻¹
Stress influence coefficient for martensite $\rho \Delta s^M$	-0.35 MPa K ⁻¹

 Table 1 - Table of properties for the SMA material model

Unlike many SMA material models, the stress values where the martensite and austenite start and finish their respective phase transformations are not directly specified. Rather, they are evaluated on the



Figure 5 - Ansys SMA material model from the ANSYS Documentation (ANSYS Inc, 2009)

stress-temperature diagram on a per temperature basis. This relationship is shown in Figure 4.

Comparison to standard ANSYS SMA model

Since ANSYS already has a SMA material model included, a comparison is warranted. The most obvious improvement over the standard ANSYS material model is the ability to model the shape memory effect since the ANSYS model deals primarily with modeling the pseudoelastic phase. The ANSYS model also only specifies one initial stiffness, that of the austenite before the start of the phase transformation. Since martensite can be significantly less stiff than austinite, the proposed model will enhance accuracy by considering this effect. The current material model can

Advanced Shape Memory Alloy Material Models for ANSYS

also model the transformation region of the stress strain models with exponential (Tanaka, 1986) or cosign models (Liang, 1992).

One capability that the Ansys model possesses over the proposed model is a parameter to specify the compressive to tensile strength ratio.

The material model has capabilities for structural and thermal capabilities and the desired physics can be employed depending on the current analysis. For a primarily structural analysis at a single temperature, the material model is compatible with SOLID185/186 elements. When temperature changes and effects need to be considered, the SOLID226/227 direct coupled elements can be used with thermal and structural physics enabled.

Uniaxial Tests

To verify the implementation of the user material model, a series of 2 element uniaxial test simulations were performed. The 1x1x1 m cube was composed of two solid226 direct coupled field elements, with the structural and thermal physics key option specified. The cube was fixed on the bottom face and tensile pressure loading was applied to the top face in each case. The nominal temperature unless otherwise specified was 325° K.



Figure 6 - Test setup, with load face and fixed degrees of freedoms indicated

Shape Memory Effect

The shape memory effect is demonstrated through a combination of temperature and structural loading. Initially, the material is at a temperature of 293° K which is between the martensitic start M^{0s} and the austenitic start A^{0s} temperatures. The material is loaded, as shown in Figure 7. Martensitic phase transformation is induced and the material partially retains the deformation with no applied load. The material is heated to above the austenitic finish temperature A^{0f} to fully recover the deformation.



Pseudoelastic Loading

At above the austenitic finish temperature A^{0f}, the material exhibits pseudoelastic behavior. The uniaxial load is applied and removed, demonstrating the hysteresis loading path in Figure 8.

Thermal Actuation

Temperature induced strain with a nominal stress load is demonstrated in this case, shown in Figure 9. Initially the material is at a temperature above A^{0f}, and small stress load (100 MPa) is applied. The material is then cooled to a temperature below the martensitic finish temperature M^{0f}, a process in which phase transformations and strains are developed. The material is then heated back to the start temperature, where a similar hysteresis load path can be observed and the strain recovered.



Stent Application

Nitinol is commonly used in self expanding (SE) stents due to its unique mechanical properties and biocompatibility. In some uses of the stent, it is thermally deployed in the body. In this process the stent is crimped into its deployment configuration at room temperature, which is typically below A^{0s}. Insertion into the blood vessel is accomplished via a catheter, with the stent temperature being controlled by cooled saline solution until it reaches the deployment site. When the stent is in the desired location, the cold saline flow is stopped and the stent heats up to body temperature. In Nitinol variants for stents, the body temperature is above the A^{0f}, and the stent will recover the residual strains and return to its original configuration. While not all SE stents are thermally deployed, there are engineering reasons to use a Nitinol variant with an A^{0f} close to the body temperature such as limiting the force it applies to the vessel wall. Temperature deployed or not, most Nitinol stents will undergo this temperature induced





phase change and the current material model provides the capability to model this process.

Stent Design

An example stent geometry was created in Autodesk Inventor 2011. This stent configuration is similar to the *zformation* stent designs commonly in use (Stoeckel, 2002). A single section was modeled and no crosslink struts are modeled or considered in this test case. The strut length is 2.25 mm, the width is 0.14 mm and the overall thickness is 0.24 mm. There are 12 occurrences of the general pattern around the diameter. The nominal inner diameter of the stent is 7.62 mm.

Simulation Setup

The simulation will cover the crimping process and thermal induced expansion of the stent into a portion of vein. The crimp tool is modeled as a rigid body and through contact will deform the stent into a crimped configuration in 293° K environment. The crimp tool will be removed from the stent, which will retain residual strain from the crimp process. After being moved into position inside the vessel, the stent is brought to 315° K, expanding it into the vessel.

The sample vessel has a nominal inner diameter of 7 mm and is 0.7 mm thick, with an inner plaque layer of 1 mm. The vessel and plaque layers are modeled as 5 and 3 parameter Mooney-Rivlin hyperelastic



Figure 11 - Full simulation load process of crimping the stent, moving it into the vein and thermally induced expansion

materials, respectively, as in (Wu, 2007). Symmetry was used to reduce the model size to a 15° representative portion, as in Figure 10. The final simulation has 162 elements in the stent and 1440 elements in the vessel.

Results/Discussion

The simulation results are presented in the following figures. The full load path is presented in Figure 11, and in more detail in Figure 13 and Figure 14. During the crimping process, the stent experiences maximum principal strains of up to 5.1% before contacting the vessel and entering a max equilibrium strain of 4.2%. The artery experiences a maximum principle strain of 7.2% while the plaque develops up to 15.5% strain, shown in Figure 14.

The stent dilates the vessel up to 0.29 mm in the radial direction, shown in Figure 12. This value is near the total stent thickness of 0.24 mm and suggests that the stent as simulated may not be stiff enough. However, the addition of struts to connect other sections of the stent may increase stiffness if they were considered in this test case.

In a shape memory alloy, it may be desirable to postprocess the material phases directly in order to gain greater insight into how it will perform. The mechanical behavior of the material is nonlinear and at any time it is based on where it is in the hysteresis load path, which is available in the form of state variables. The martensitic volume fraction of the stent, shown in Figure 13 and Figure 14, tells part of the story. Also available are phase change state indicators, such as the whether or not transformation is occurring and in what direction.

In conclusion the current, newly implemented material model offers new possibilities for simulation as well as enhanced simulation capabilities for existing applications in the pseudoelastic region. For more information about the capabilities and availability of the material model featured, visit <u>Ozen Engineering</u> <u>Inc</u> or contact us at <u>info@ozeninc.com</u>.



Figure 12 – The radial deformation on a 1/24th section of the vessel & plaque

Advanced Shape Memory Alloy Material Models for ANSYS



Figure 13 - Crimp process details showing (from top to bottom) the 1st principle elastic strain, the Maximum 1st principle strain on the stent, the maximum crimping pressure and the martensitic volume fraction. The contour plots are each at t = 0, 0.5, 1.0, 1.5

Advanced Shape Memory Alloy Material Models for ANSYS



vessel and plaque, the temperature of the stent and the martensitic volume fraction. The contour plots are at t = 3, 3.50, 3.75 and 4



Bibliography

ANSYS Inc. (2009). Ansys 12.1 Help. Canonsburg, Pennsylvania.

Duerig, T. W. (2000). An overview of superelastic stent design. *Min Invas Ther & Allied Technol 9(3/4)*, 235-246.

Lagoudas, D. C. (1996). A unified thermodynamic constitutive model for SMA and finite element analysis of active metal matrix composites. *Mech. Composite Mater. Struct. 3*, 153-179.

Liang, C. (1992). A multi-dimensional constitutive model for shape memory alloys. *Journal of Engineering Mathematics 26*, 429-443.

Stoeckel, D. (2002). A survey of stent designs. *Min Invas Ther & Allied Technol 11(4)*, 137-147.

Tanaka, K. (1986). A thermomechanical sketch of shape memory effect: One-dimensional tensile behavior. *Res Mechanica 18*, 251-263.

Wu, W. (2007). Delivery and release of nitinol stent in carotid artery and their interactions: A finite element analysis. *J Biomech* , 3034-3040.