Analysis of Shape Memory Alloy Actuator

[1]Dixit Pratik P., [2]Dr. Kotwal Girish N.
[1]P.G. Student, [2]Head of the Department, Production Engineering,
[1] Mechanical Engineering,
[1]Vishwakarma Institute of Technology, Pune, India.

Abstract : Shape Memory Alloys have a unique property to recover their original shape on heating and withstand large deformations without undergoing plastic deformation; hence they can be used as efficient actuators. This paper studies their application in switches of structures with remote deployment. This work evaluates the stress and heat induced change of phase in a SMA, in terms of the transformation strain tensor. FEA tool, ANSYS APDL, has been used to perform a 2-D analysis of a Cu-Al-Zn-Mn SMA specimen subjected to loading in two steps with mechanical and heating loads.

***IndexTerms* - Austenite, Martensite, Shape Memory Alloy, Transformation Strain.**

I. INTRODUCTION

"Shape memory" name is derived from its ability to remember original shape. On loading at lower temperatures, the material gets deformed and even though the load is removed it remains deformed. To return to its original size and dimensions it needs to be subjected to a certain temperature [1].

II. THEORY OF SHAPE MEMORY ALLOYS

Phase Conversion in SMAs

Fig. 1 shows the phase conversion of austenite to twinned martensite to detwinned martensite. SMA has Austenite as a parent phase. Austenite to martensite transition is called as forward conversion. This conversion takes place as the material is cooled to the lower temperatures .The material transforms back to austenite if the same material is heated; this conversion is called as reverse conversion. The phase conversion is induced either by a temperature change or by application of stress.

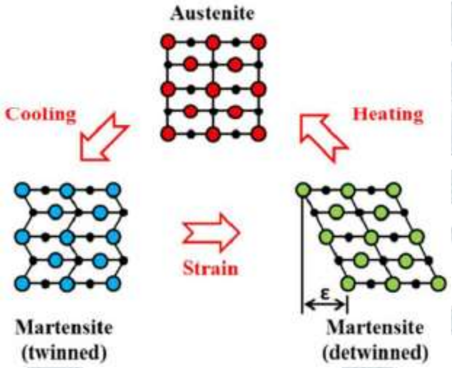

Figure 1 Physical phase Transformation in SMA [1]

Phase Conversion with Change in Temperature

The SMA has its phase conversion associated with four particular temperatures. Firstly, material is regarded to be in austenite phase at stress free state. Incidentally, as the material is cooled, the temperature first reaches martensite start temperature (Ms). Thus the martensite phase leads to a mixture of martensite and austenite.

As the material is cooled further, the temperature attains martensite finish temperature (Mf) where the phase of the material is completely twinned martensite. During the conversion of austenite to twinned martensite, the martensite is formed by twinning. The overall strain energy due to conversion is minimized during the twinning, hence no shape change occurs. When the same material in twinned martensite phase is subjected to heat, the temperature initially attains austenite start temperature (As), which begins the austenite phase. As the material is cooled further, the temperature reaches martensite finish temperature (Mf), the state in which the material is completely twinned martensite. The martensite formed occurs by twinning and arrange itself to minimize overall strain energy due to conversion, hence the shape remains the same.

Similarly, as the twinned martensitic structured SMA is exposed to heating and its temperature is raised up to austenite start temperature (As), so austenite phase is developed in it. When the temperature is elevated further, the temperature initiates austenite finish temperature (Af), and this is where the material is complete austenite. Fig. 2 shows schematics of phase transformations at respective temperatures.

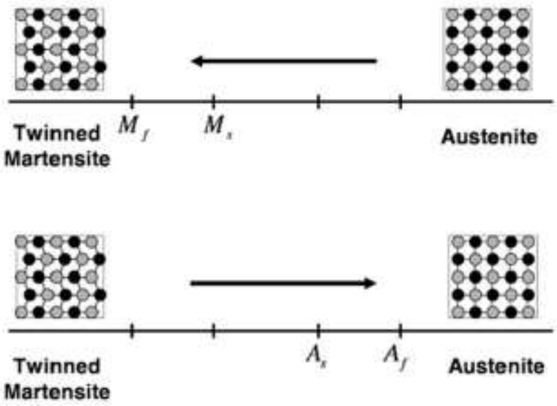

Figure 2 Transformation of material phase [1]

Shape Memory Effect (SME) in SMAs

The Shape Memory Effect is well explained in the Fig. 3 below. When the material is loaded at point B, which is below the Mf, the stresses in the it attains σs i.e. detwinning start temperature. When loaded further the stress reaches σf i.e. detwinning finish temperature, hence the crystals in the material are transformed to detwinned martensite. On further loading the material remains in detwinned martensite phase reaching point C. As the load is removed the material stays in deformed state at point D.

Further if the material is heated beyond austenite start temperature (As), the shape recovery starts. As the material reaches austenite finish temperature (Af), original material shape is recovered and it is completely converted to austenite phase. This behavior is called the "SME". [1]

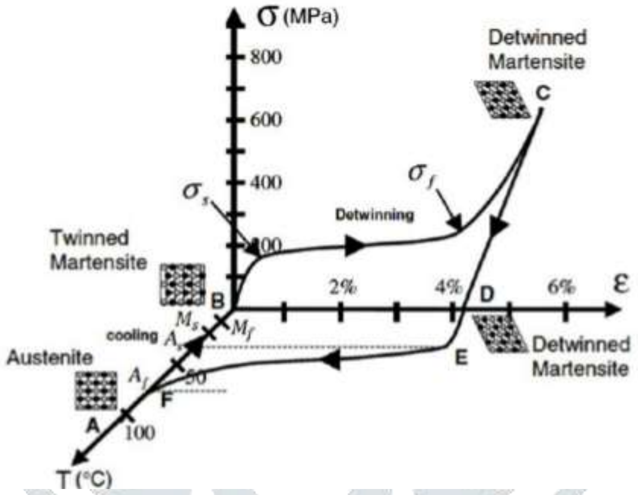

Figure 3 Shape Memory Effect of SMA [1]

III. SMA ACTUATOR PRINCIPLE

A double notched specimen is used in this study that can be used as a release mechanism for an enclosure for deployment. This SMA actuator is fixed at one end and pulled towards the enclosure to lock it. To open the enclosure the SMA specimen should be fractured. Thus for the fracture it is heated above Austenite Finish Temperature. The detwinned martensite crystals structure tries to convert to austenite structure as the temperature reaches austenite finish temperature. Volume occupied by the Austenite crystals is less as compared to detwinned martensite crystals. Hence as the material transforms to austenite, the specimen shrinks, but as the specimen is constrained; high magnitude of stresses are induced in the specimen. When the stress reaches the ultimate tensile stress the material fails. [5] The SMA Actuator is as shown in the Fig. 4[5]

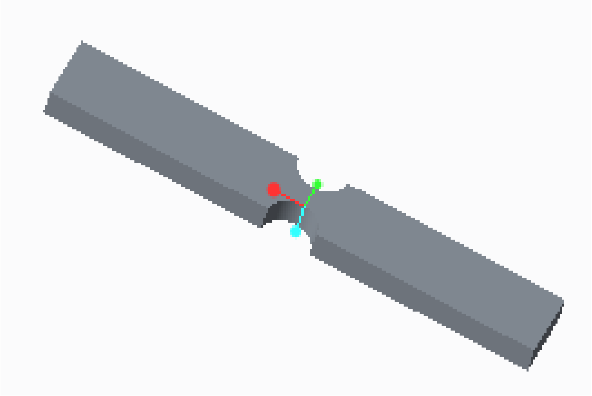

Figure 4 SMA Actuator Specimen

IV. ANALYTICAL CALCULATIONS OF PHASE TRANSFORMATIONS

The main goal of the approach used in the paper is to evaluate the different phases and corresponding residual strain in the specimen. In this model, the local thermodynamic state of the material is defined by the strain [2], which is given by;

$$\in = \in e + \in t \qquad (1)$$

Where ∈t denotes transformation strain which is defined as the strain developed due to phase transformation and ∈e denotes elastic strain.

The transformation strain (||eT||) is calculated from the equation (3) as the difference between the modulus of total mechanical strain (||etot||) and elastic strain (||el||).

$$||e_T|| = ||e_{tot}|| - ||e_l|| \qquad (2)$$

The total strain tensor etot is given by,

$$\mathrm{etot} = \sqrt{\mathrm{e11}^2 + \mathrm{e22}^2 + 2 * \mathrm{e12}^2} \qquad (3)$$

Similarly, Elastic strain is given as,

$$\mathrm{el} = \sqrt{\mathrm{e11el}^2 + \mathrm{e22el}^2 + 2 * \mathrm{e12el}^2} \qquad (4)$$

Where, e11el, e12el, e13el are the deviatoric elastic strains in x, y and xy directions.

As the SMA specimen is loaded mechanically, if the transformation strain is zero, the material at that region is regarded to be in twinned martensite phase. At the maximum value of transformation strain, the material phase is considered to be pure detwinned martensite. If the value of transformation strain is in between the lower and upper limits of transformation strain than, the material is considered to be mixture of twinned and detwinned martensite.

For the fracture of SMA specimen it is heated after application of mechanical loading. As the material is heated when in detwinned martensite phase it transforms to austenite phase. The Austenite phase being stable at higher temperatures it is considered as parent phase and martensite phase thus it is considered to be product phase. Hence if the magnitude of transformation strain is zero the material is in austenite phase. If magnitude of transformation strain is maximum, then the phase is in detwinned martensite phase. If the transformation strain value falls between the range of zero and the maximum transformation strain, the material is considered to be mixture of twinned martensite, detwinned martensite and austenite.

V. FINITE ELEMENT MODELING OF SMA

ANSYS is used to evaluate the phase transformations, stresses and corresponding strains in the SMA specimen. Thus the Specimen is initially mechanically loaded followed with thermal loading. Thus the martensite and Austenite phases are identified in the specimen. The behaviors of Cu-Al-Zn-Mn alloy are defined by a set of material parameters, which are estimated from the experimental data on NiTi alloy in the pseudoelastic phase and stress-temperature phase. [2, 3, 4]

The Cu-Al-Zn-Mn SMA specimen is described by following set of parameters:

Table 1 SMA Parameters

Constant	Value
C1	9230 MPa

C2	253.15 K
C3	73.4 K
C4	4.2 MPa
C5	0.1
C6	30.7×10^3
C7	0

The constants in Table represent,
C1- Hardening parameter
C2- Reference temperature
C3- Elastic limit
C4- Temperature scaling parameter
C5- Maximum transformation strain
C6- Martensite modulus
C7- Symmetric behavior

The specimen considered for analysis is a 2-D specimen with length 100 mm and width 15 mm. It is provided with notches of radius 5 mm. Plane strain conditions are assumed in the analysis. The other conditions in the plane strain are:

$$\varepsilon_z = \gamma_{xy} = \gamma_{yx}$$

$$\tau_{xy} = \tau_{xy}$$

Meshing is done with 2-D Plane 182 quadrilateral elements as shown in Fig. 5. These elements consist of four nodes with two degrees of freedom at every node. The specimen is meshed with an element size of 0.5 mm. The geometry is meshed which generated 5940 nodes and 5697 elements.

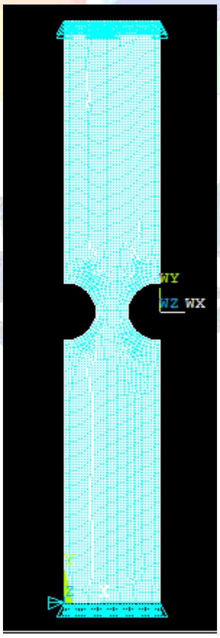

Figure 5 2D Notch Geometry

Boundary Conditions:

In this problem, following boundary conditions are defined,

$$Ux\ (x = 0, y = 0) = 0;\ Uy\ (x = 0, y = 0) = 0; \qquad (5)$$

$$Uy\ (x, y = 0) = 0 \qquad (6)$$

Which states, at the origin (x,y) =(0,0) the specimen is fixed. The bottom surface of the specimen (y=0) is freezed in y-direction, as shown in Fig 5.

In load step 1, displacement is applied to topmost end to simulate mechanical strain as shown in Fig. 5, while in load step 2; uniform temperature is applied to entire specimen.

VI. RESULTS

The contour plots for total mechanical strain and elastic strain are as shown in Table 2 after application of 6.5 mm displacement in load step 1.

Table 2 Total mechanical strain and elastic strain after Load step 1

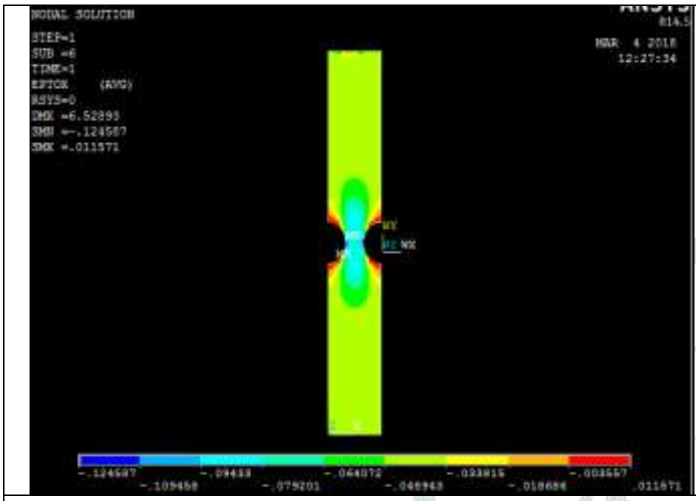	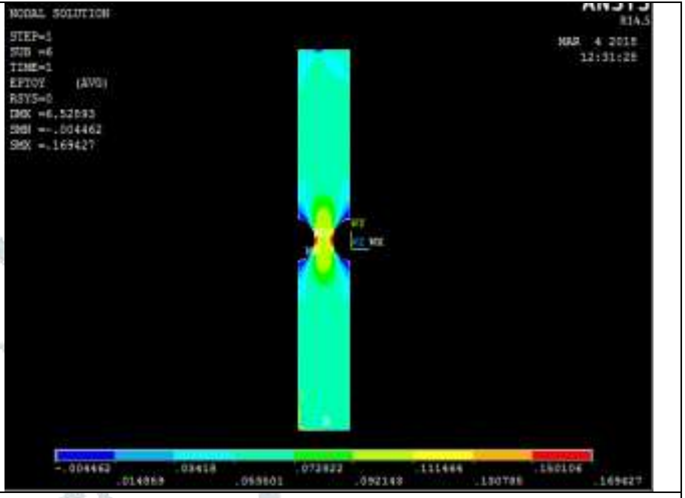
Fig.6 Total normal strain in x direction	**Fig.7 Total normal strain in y direction**
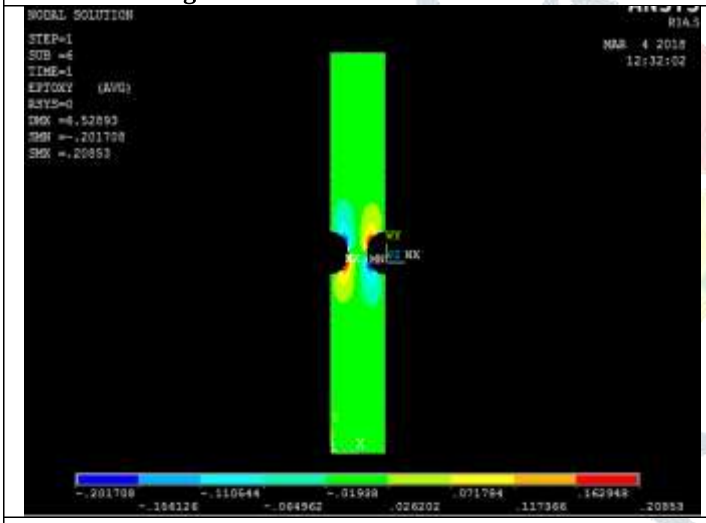	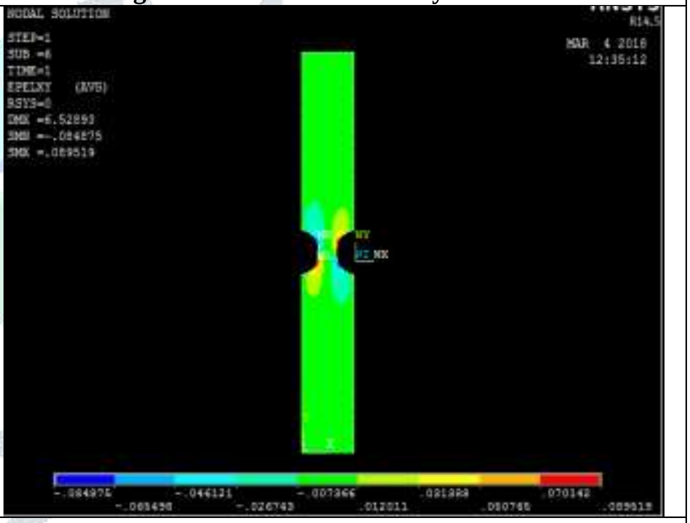
Fig.8 Total shear strain in xy direction	**Fig.9 Elastic normal strain in x direction**
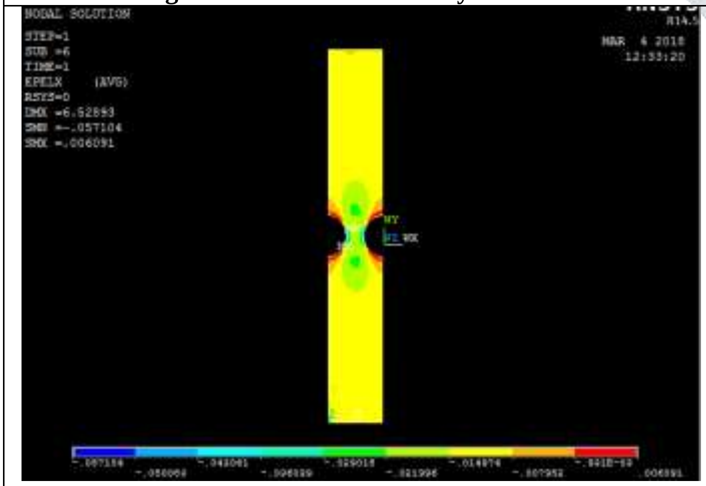	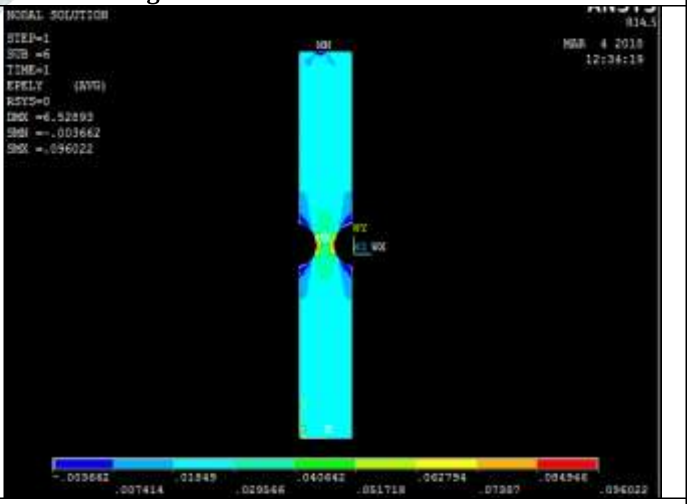
Fig.10 Elastic normal strain in x direction	**Fig.11 Elastic normal strain in y direction**

Similarly contour plots for load step 2 are plotted to obtain mechanical strain and elastic strain after application of uniform temperature of 1250 K in Table 3.

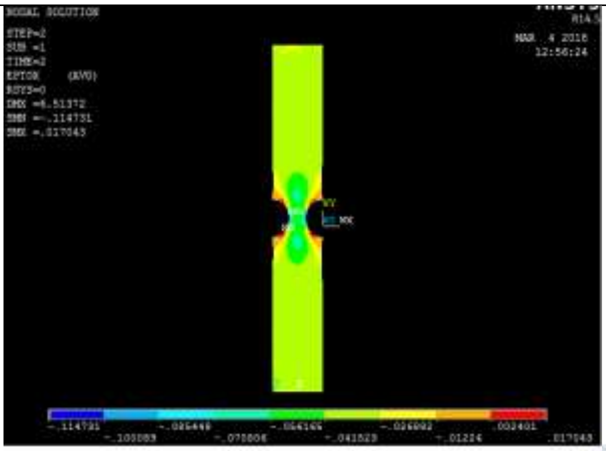	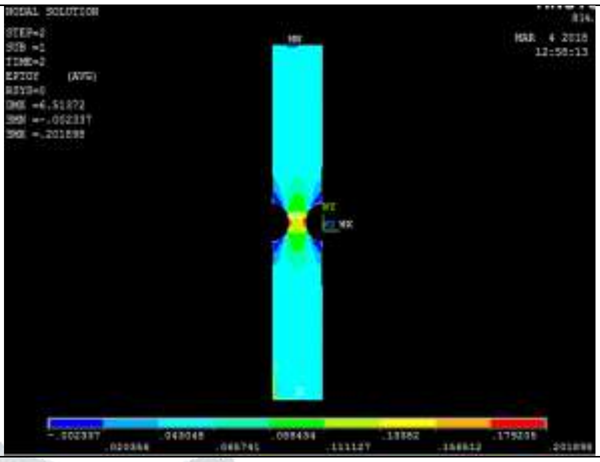
Fig.12 Total normal strain in x direction	**Fig.13 Total normal strain in y direction**
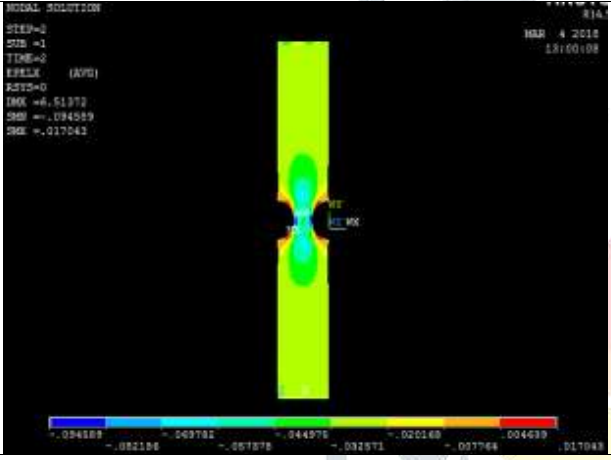	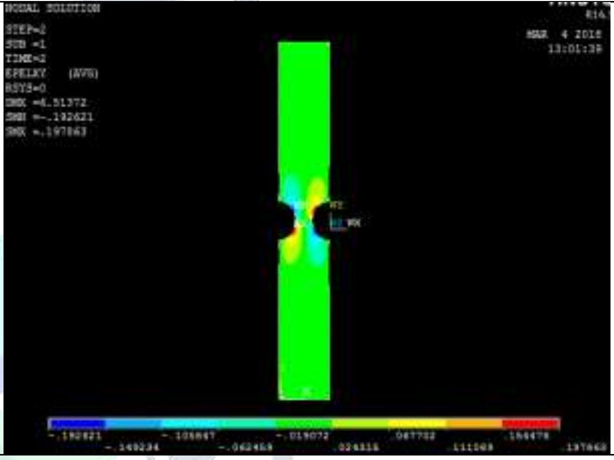
Fig.14 Total shear strain in xy direction	**Fig.15 Elastic shear strain in xy direction**
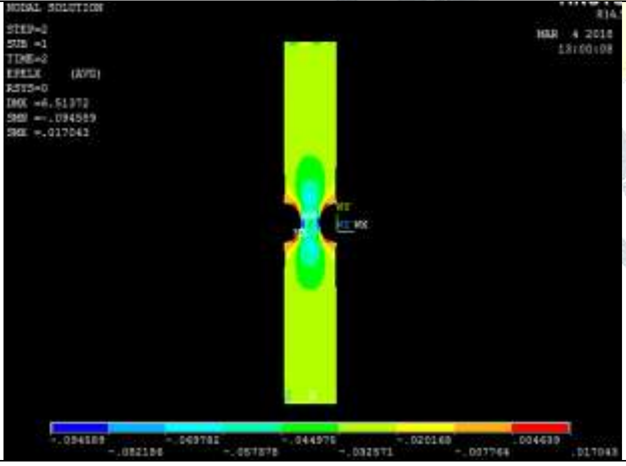	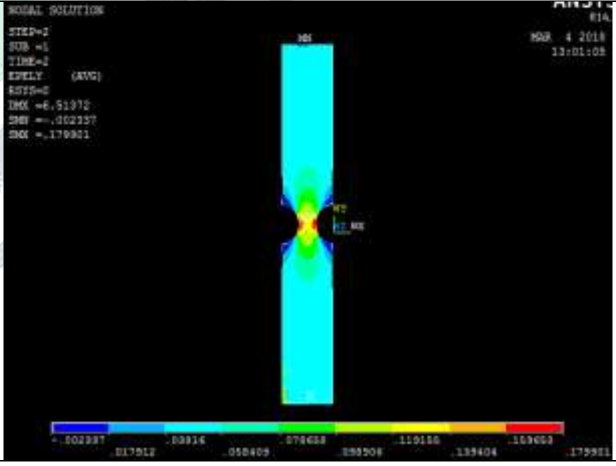
Fig.16 Elastic normal strain in x direction	**Fig.17 Elastic normal strain in y direction**

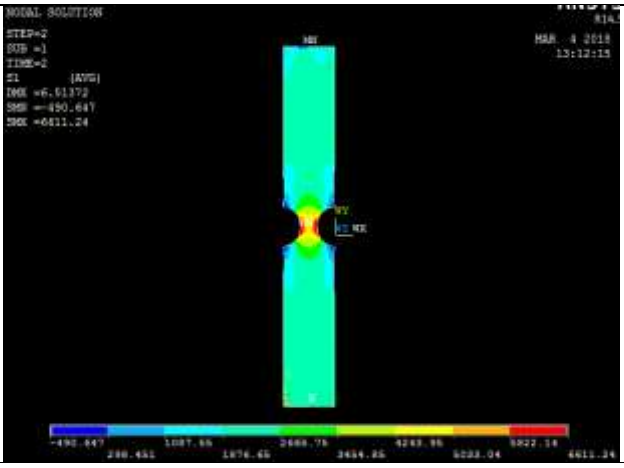

Fig.18 Principle stresses at load step 1

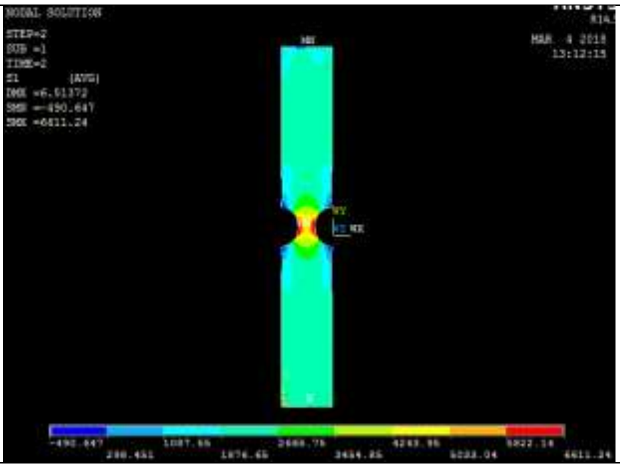

Fig.19 Principle stresses at load step 2

Thus the transformation strain is calculated from the equations (1), (2), (3), (4) at mid node between the two notches for displacements of 3mm, 4mm, 5mm, 6.5mm and the results are as tabulated in table 4.

Table 3 Transformation strain and Principal stresses in SMA for 2 Load steps

Displacement(mm)	**3**		**4**		**5**		**6.5**	
Load step	***1***	***2***	***1***	***2***	***1***	***2***	***1***	***2***
Transformation strain	0.0464	0	0.0612	0	0.0731	0	0.0856	0
Principal stresses(N/mm^2)	951.96	2293.3	1200	3057.6	1406.4	3822	1667.8	4984.6

Thus from the table it is clear that at end of load step 1 at each displacement the transformation strain is in between zero and maximum, indicating that the specimen has both detwinned martensite as well as twinned martensite phase. Also as the displacement is increased the transformation strain tends to increase to maximum which shows the detwinned martensite phase is increasing with the displacement.

In the load step 2, it is found that the value of maximum principal stress is almost twice the value of principal stress in load step 1. This occurs as the specimen is heated the crystal structure in it is transformed to austenite. The lattice of Austenite is cubic structured; hence it occupies less volume as compared to the orthorhombic crystal structure of detwinned martensite. Thus, in austenite phase the specimen tries to shrink. But, as the specimen is constrained, it is unable to shrink. Due to which high stresses are generated in the specimen causing it to fracture.

Thus in physical application, the SMA Actuator is fixed at one end and stretched on the other end to fix on the structure to be deployed. This induces mechanical strain in the Actuator. As the Actuator is heated by passing electric current, it fractures due to increase in the stress levels, which releases the structure to be deployed.

VII. CONCLUSION

In this work material phases are estimated in terms of transformation strain. The specimen is loaded in two steps. The results are obtained in form of contour plots of principal stresses, total and elastic mechanical strain at the end of each load step. The behavior of transformation strain and principal stresses is studied for different displacements. Thus the SMA Actuator fracture is simulated through FEA software.

REFERENCES

[1] Kumar. P. K., Lagoudas. D. C: “Introduction to Shape Memory Alloys. In Shape Memory Alloys”. Springer US: 2008. Vol. 1, pp 1-51.
[2] Angela C. Souza, Edgar N. Mamiya, Nestor Zouain: “Three-dimensional model for solids undergoing stress-induced phase transformations”.
[3] Auricchio. F: “A Robust Integration-Algorithm for a Finite-Strain Shape-MemoryAlloy.” International Journal of Plasticity. 17 (2001): 971-990
[4] Auricchio. F, Taylor. R. L, Lubliner. J: “Shape-Memory Alloys: Macromodeling and Numerical Simulations of the Superelastic Behavior.” Computational Methods in Applied Mechanical Engineering. 146, 1 (1997): 281-312
[5] C. Mavroidis – “Development of Advanced Actuators Using Shape Memory Alloys and Electrorheological Fluids” Robotics and Mechatronics Laboratory, Department of Mechanical and Aerospace Engineering