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CREEP ANALYSIS OF BIMATERIAL MICROCANTILEVER BEAM FOR SENSING DEVICE USING ARTIFICIAL NEURAL NETWORK (ANN)

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ABSTRACT

In this study, a feed-forward back-propagation Artificial Neural Network (ANN) is used to predict the stress relaxation and behavior of creep for bimaterial microcantilever beam for sensing device. Results obtained from ANSYS® 8.1 finite element (FE) simulations, which show good agreement with experimental work [1], is used to train the neural network. Parametric studies are carried out to analyze the effects of creep on the microcantilever beam in term of curvature and stress developed with time. It is shown that ANN accurately predicts the stress level for the microcantilever beam using the trained ANSYS® simulation results due to the fact that there is no scattered data in the FE simulation results. ANN takes a small fraction of time and effort compared to FE prediction.

1. INTRODUCTION

Micro-cantilever is widely used in Micro-Electro-Mechanical-System (MEMS) due to its versatile application, high sensitivity and fast response. Bimaterial microcantilever beams are used as the main drive to measure deformation. The applications of metal/silicon icrocantilever include infrared light detection, microcooling devices, biosensor, photothermal sensing/ actuation, optics, microelectronic switching, micromanipulation and chemical sensing. The abovementioned MEMS utilize the bending displacement of the microcantilever to facilitate transduction for sensing or actuation. The means to induce bending in bimaterial microcantilevers depends on its particular application [1 - 3].

Creep, which is the interest of this research, is one of the most important issues in the reliability of MEMS. Creep as a function of stress, σ, time, t and temperature, T, is the permanent elongation of component under a sustain load maintained for a period of time. It occurs even if the load is small enough so that the yield strength is nowhere exceeded. Creep manifests itself at temperatures above 0.3 T_m, where T_m is the absolute melting temperature, and the influence of creep strain becomes considerable around 0.5 T_m. The amount of creep depends on the geometry

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of the samples. Creep of silicon and other materials becomes much more serious for thin cantilever beam [5 - 9].

Creep and/or stress relaxation may happen on bimaterial cantilevers containing a metallic layer. Contraction of the metallic layer, due to a difference in the coefficient of thermal expansion between metal and silicon or a time-dependent inelastic strain in the metallic layer, would affect a change in the curvature of the bimaterial beam. Regardless of the MEMS application, it is critical for bimaterial microcantilevers to exhibit consistent and predictable displacements over time. The creep phenomena pose a serious reliability concern since they operate at relatively low stresses and their displacements are very sensitive to small inelastic strains in the metallic layer [3 - 5].

Experimental analyses of creep behavior on microcantilever have been carried out by several groups [3 - 5, 10 - 22]. However, finite element simulations on the behavior of creep in microcantilever are very limited. This simulation work is useful to understand the behavior of microcantilever in its working environment and to predict creep behavior in microcantilever since experimental work is costly in term of material, time and money. These simulations can help in preventing creep failure in any new MEMS device using microcantilever with the given necessary properties.

In this paper, an ANSYS® 8.0 finite element analysis (FEA) is used to simulate and analyze the stress relaxation and behavior of creep for bimaterial microcantilever beam for sensing device. Simulation results from the finite element analysis is then used for training using ANN with MATLAB® 7.0 so that the creep and stress relaxation behavior in the bimaterial microcantilever can be easily predicted for other design parameters.

1.1. Modeling and Prediction by Using FEA

In order to train the ANN, simulation using ANSYS® 8.0 was carried out to provide database. A finite element model has been built based on the experiment carried out by Yanhang Zhang and Martin L. Dunn [1]. This model is analyzed based on the experimental data for the linear and geometric nonlinear behavior of bimaterial microcantilever subjected to thermal loading due to the combined creep and stress relaxation. Simulation result for stress is used to check whether the stress developed exceeds its yield strength. Curvature of microcantilever is also determined.

A 2-D modeling of the Au/Si microcantilever beam is simulated and analyzed. It has an overall size of 280 μm (*l*) × 50 μm (*w*) × 2 μm (which thickness of 0.5 μm in gold and 1.5 μm in polysilicon), similar to the model and conditions used for the experimental study [1]. The cantilevers were held at the modest temperature of 120°C. The polysilicon will deform elastically at this temperature, and will not affect the creep and/or stress relaxation of the gold layer. The stress relaxation process is modeled by taking a simple power law in the gold,

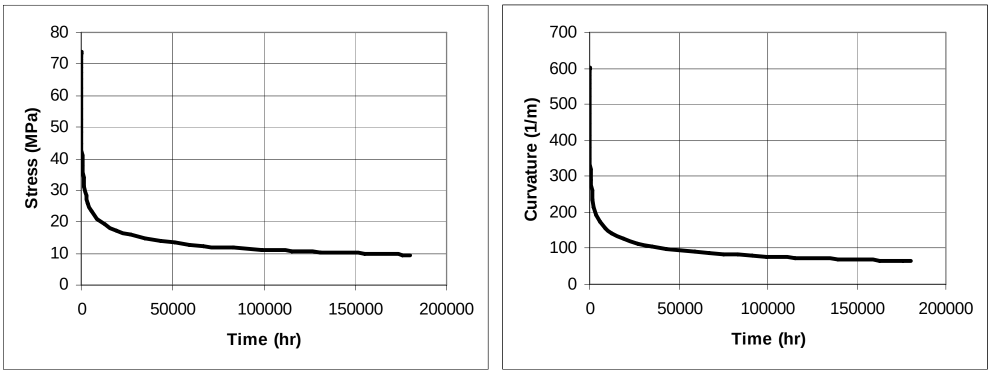
$$\dot{\varepsilon} = A\,\sigma^{n}$$

where: $\dot{\varepsilon}$ = strain rate [s^{-1}]; σ = stress [MPa]; A and n = creep constant.

From the experimental work, the relaxation data is found to be as n = 5 [1] but the actual value of A depends on the film thickness with some unknown relationship. Inelasticity in the Au film is observed to be stress relaxation. In this study, the creep constants, n and A is taken to be 5 and 5.2×10^{-15} $hr^{-1}MPa^{-5}$ respectively as found from the experimental study [1]. The ANSYS simulation result shows a good agreement with the results obtained experimentally as shown in Table 1. Based on this result, parametric study is then carried out.

Table 1: Comparison of experimental results with Finite element simulation (ANSYS) results of stresses in Microcantilever beam with the dimension of 280 μm × 50 μm

Time (hr)	Stress (MPa)		Error (%)
	Experiment result [1]	ANSYS	
0	80	74	7.5
160	50	52	4
428	41	42	2.4
684	38	38	0



(a) (b)

Fig. 1: *ANSYS Result*

The graph of stress and curvature on the microcantilever against time (15 years) resulting from the nonlinear static analysis is shown in Figs. 1a and 1b, respectively. Both the stress and curvature decreases with time. The microcantilever behaves in neither creep nor stress relaxation since none of stress or strain is constant. It shows combination of both creep and stress relaxation.

1.2. Prediction by using ANN

The working process of ANN is based on decision making process in human brain. It is categorized under artificial intelligence method and has been applied in many different fields such as control, finance, aerospace, engineering, industrial and manufacturing [23 - 26]. Typical neural network consists of sets of input, sets of output and weighting function. Neural networks are trained, to perform a particular function by adjusting the values of the connections (weights) between elements, based on a comparison of the output and the target, until a particular input leads to a specific target output. Such a situation is shown in Fig. 2. Once the network is trained, it can then be fed with any unknown input and is expected to predict the output with a high degree of accuracy.

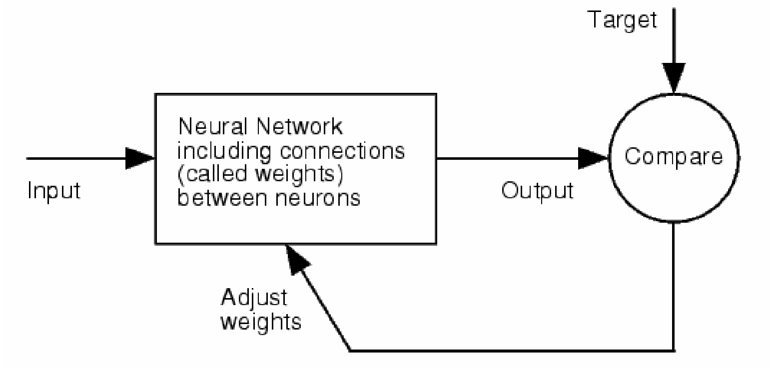


Fig. 2: *Neural Networks training process*

In this work, the neural network has been trained using feed-forward back-propagation. The back-propagation uses supervised learning, which means that the example of input and the target output data are provided for computation, and then the error between the output and the target is calculated. The idea of back-propagation is that the training begins with random weights and the goal is to adjust them so that the error will be minimal. Back-propagation can train multilayer feed-forward networks with differentiable transfer functions. A feed-forward network is made up of one or more hidden layers of sigmoid neurons followed by an output layer of linear neurons. Multiple layers of neurons with nonlinear transfer functions allow the network to learn nonlinear and linear relationships between input and output vectors. Each layer of the network has a number of nodes connected with each other layers. Each of the first later obtains some information signals from the input layer nodes and then the output of the layer feed some information signals into the second layer nodes and so on.

During the training process the information flow is only allowed in one direction that is from the input layer to the output layer through the hidden layers. The network consisting of three layers with four neurons in the input layer, ten neurons in the hidden layer and one neuron in the output layer as shown in Fig. 3, is used in this study. 300 set of data have been taken for the training purpose. Time, beam length, beam width, and Length/Width ratio are taken as the input, whereas creep stress or curvature is taken as the output.

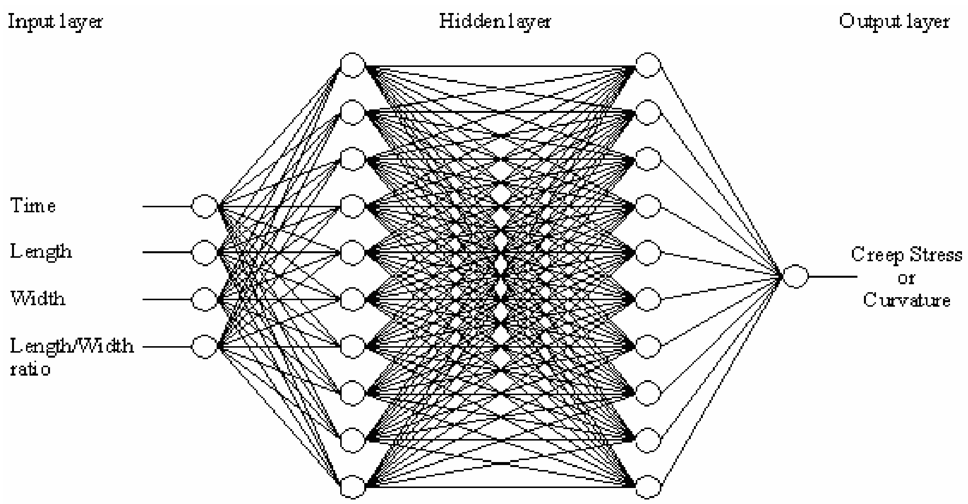


Fig. 3: *Illustration of neuron network used in this study*

The simulation results of the creep stress obtained from the FEA is used to train ANN. However, results for 3 years (26280 hrs) and 10 years (87600 hrs) will not be used as input parameters to the ANN. Those simulation data will be used later to verify the accuracy of the ANN results when compared to the FEA modeling simulation results. The range of input parameters investigated using the ANN for the prediction of the creep stress is shown in Table 2. The ANN analysis was set with 1000 epochs to convergence. Simulation with ANN takes less than 1 minute by using Pentium IV CPU 3.0 GHz. Whereas, for FEA modeling more than 15 minutes per simulation for each set of input parameter and approximate 5 hour need to predict the creep relaxation with difference input geometric.

Table 2: *Range of input parameters investigated in ANN*

Parameters	Range
Time (hrs)	0 – 131400 (15 years)
Beam length, *l* (μm)	50 – 1000
Beam width, *w* (μm)	5 – 500
Length/Width ratio	0.28 - 20

2. RESULTS AND DISCUSSION

Table 3: *Comparison of FEM simulation and ANN prediction with different layers for different values of parameters*

Time (yrs)	Width, *w* (mm)	Length, *l* (mm)	Creep stress (MPa)				Percentage error (%)		
			ANSYS	ANN 4 layer	ANN 3 layer	ANN 2 layer	4 layer	3 layer	2 layer
3	50	50	15.42	15.396	15.392	15.497	0.1530	0.1790	0.5006
		100	15.79	15.750	15.750	15.789	0.2565	0.2540	0.0063
		150	15.88	15.850	15.846	15.894	0.1864	0.2160	0.0869
		200	15.91	15.881	15.880	15.933	0.1816	0.1917	0.1433
		250	15.93	15.895	15.896	15.949	0.2228	0.2116	0.1180
		500	15.96	15.935	15.925	15.983	0.1566	0.2199	0.1447
10	50	280	11.53	11.523	11.530	11.532	0.0572	0.0035	0.0182
	100		11.5	11.474	11.496	11.505	0.2278	0.0330	0.0452
	150		11.44	11.419	11.430	11.459	0.1818	0.0874	0.1661
	200		11.37	11.359	11.357	11.385	0.1003	0.1143	0.1310
	280		11.24	11.252	11.239	11.258	0.1094	0.0133	0.1610
	500		10.97	10.961	10.957	10.989	0.0784	0.1158	0.1696
Average error							0.1593	0.1366	0.1409
Processing time							~2 min	~1 min	~30 sec

Comparisons of results of creep stress of microcantilever generated from FEA and ANN are presented in Table 3. ANN results with 2, 3 and 4 layers with the time taken to complete the analysis have also been shown. From this analysis, the ANN with 3 layers is chosen because of its accuracy and reasonable time taken. The FEA simulation results are shown for variation either on the width or length within the range of 50 µm to 500 µm while the fixed value of the width and length are set at 50 µm and 280 µm respectively. Comparisons are made for analyses with time duration of 3 years (26280 hrs) and 10 years (87600 hrs) without any external force applied on the microcantilever beam. The percentage of errors is less than 1% for those difference numbers of layer. ANN model with three layers gave the low value in percentage error and good processing time. Three layers ANN predictions have been carried on for curvature prediction. With this negligible error, it has been proven that the trained ANN is able to predict accurately the creep stress of the microcantilever beam.

Figure 4 shows the comparison of the creep stress and curvature obtained using ANN with the finite element analysis solution. Prediction for 3 year and 10 year are shown. Fig. 4a and 4b show the effect of beam length on creep stress and curvature respectively. Fig. 4c and 4d show the effect of beam width on creep stress and curvature respectively.

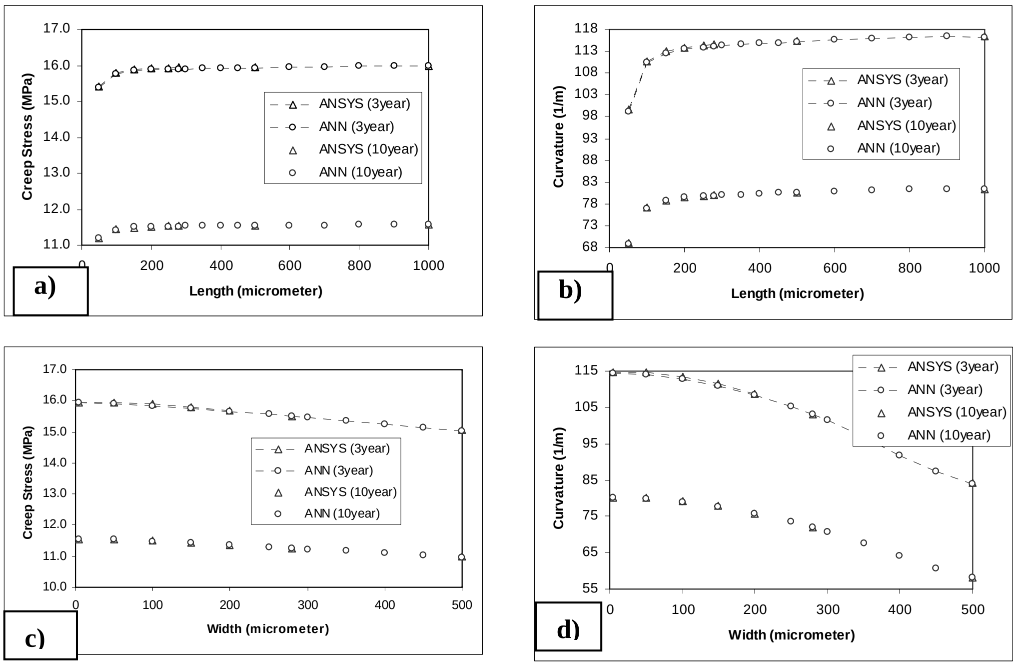


Fig. 4: *Comparison of simulation result obtained using ANN with the FEA. (a) The effect of beam length on creep stress (b) The effect of beam length on curvature (c) The effect of beam width on creep stress (d) The effect of beam width on curvature*

Figures 4a and 4b shows the effect of beam length on the creep stress and curvature in microcantilever receptively, with the width fixed at w = 50 µm for 3 year and 10 year time. The entire graphs showed the same shape, the creep stress and curvature increase with increasing the beam length for beam shorter then 150 µm, however it can be clearly seen that increasing the length in microcantilever does not bring any significance effect on the microcantilever creep behavior especially for the length of more than 150 µm. Besides, the creep stress and curvature decrease with time.

Figures 4c and 4d shows the effect of beam width on the creep stress and curvature in microcantilever receptively shows, with the length fixed at l = 280 μm for 3 year and 10 year time. The entire graphs showed the same shape. Based on the graph shown in those figure, it can be observed that the increase in the width of the microcantilever resulted in a significant decrease of stress for the microcantilever creep behavior. The slope increases from 0 μm width until 280 μm width, and then decreases. Thus, increasing the width brings significant effect to the beam creep behavior especially if the width is reduced to a value smaller than its length (< 280 μm). Comparing the results for both varied length and varied width analysis, it can be noted that microcantilever with higher length or lower width will have higher value of creep stress.

Simulation result generate by ANN show good accuracy with ANSYS simulation in the entire graphs with a small percentage of error (< 1%). Therefore, ANN is capable of providing high accuracy result.

3. CONCLUSIONS

A finite element modeling using ANSYS® 8.0 has been used to simulate and analyze the creep and stress relaxation of bimaterial microcantilever beam. The present simulation was able to produce results on the stress relaxation which is similar to the previous experimental work done [1]. The predicted parameter included stress and curvature of the bimaterial microcantilever. Stress in bimaterial microcantilever can be used to check weather exceed its yield strength. Curvature of microcantilever was determined for predict its performance. It has also been shown that ANN used in the analysis is capable of accurately predicts the creep stress on the microcantilever beam using the trained FEM simulation. This would be a very useful tool particularly to assist in the design of the microcantilever beam.

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