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Abstract: *Steel and copper are the most widely used materials around the world. In this work, the tip deflection of a fixed-free support Copper-Steel bimetallic strip is simulated using Fuzzy Logic and ANSYS Static Structural. Copper-steel is a very popular bimetal and is used widely in different fields of technology. For Fuzzy simulation, Tip Deflection Fuzzy Logic Controller (TDFLC) is designed with three inputs as T.Diff, Thickness, and Length while T.Deflection as output. For input values of T.Diff (278 °C), thickness (1.4 mm) and length (120 mm) TDFLC generates T.Deflection of 12.8 mm with an error of 1.59%. For real-time simulation, the geometry of dimension 120×7×1.4 mm is designed by ANSYS. At the temperature difference of 278 °C, ANSYS results are 12.8 mm with an error of 1.59%. The results concluded that the tip deflection is inversely related to thickness while in direct relation with both temperature difference and Length of bimetal.*

Keywords: Copper-Steel; Bimetal; Tip deflection; Bimetallic strip; Fuzzy Logic Controller

1. INTRODUCTION

Steel and copper are the most widely used materials around the world. With the advancement in science and technology, individual materials or single alloys are not enough to meet the requirements of engineering and industry. Bimetals are an excellent replacement for individual materials. Bimetals are composed of two different materials with different physical and chemical properties. Thus, they not only reduce the weaknesses of the individual materials but also are cost-effective and have more additional properties. Copper-steel is a very popular bimetal and is used widely in different fields of technology. Copper-steel bimetals are commonly used in industry and engineering fields as pipeline tubes, bimetallic sheets, wires, bearing brushes, and other components of engineering machines [1]. As lead is harmful to both human health and the environment, so its use is decreasing day by day. Copper-steel bimetal is also an excellent replacement for lead [2, 3].

Bimetals are composites comprise of two layers of different materials with different coefficients of thermal expansion [4]. Bimetal beams are highly sensitive to thermal conditions and bend with temperature changes. The least value of heat change that a bimetallic cantilever can detect lies in the range of femtojoule [5]. This bimetallic effect is based on S. Timoshenko's theory of bimetallic strip thermostats [6]. When a bimetallic beam observes the temperature change, the layer with higher C.T.E or active layer tends to elongate more than the layer with lower C.T.E or passive layer. This causes tension in the passive while compression in the active layer. Due to these compression and tension forces, bimetal tend to bend toward the passive layer [7].

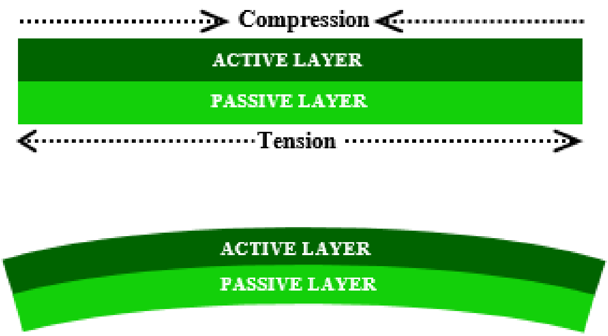


Fig. 1. Bimetallic effect in Bimetallic beam

Bimetals with one end fixed to support and the other end free to move are also used in electric switches for avoiding over-currents (7). For a fixed free end bimetal beam the tip deflection can be calculated by the formula

$$\delta = \frac{f\,\Delta T\,L^2}{h} \tag{1}$$

Where δ is tip deflection, ΔT is the temperature difference, L is the length of beam and f is the specific deflection of the bimetal composites. Specific deflection depends on the materials used for making bimetal and the ratio of the thickness of the individual layers of the bimetal. Specific deflection of the bimetal composite can be measured by using the formula

$$f = \frac{1}{2}\left(\frac{6(\alpha_2-\alpha_1)(1+m)^2}{3(1+m)^2+(1+m\cdot n)(m^2+\frac{1}{m\cdot n})}\right) \tag{2}$$

Where $\alpha_2 - \alpha_1$ is the difference between coefficients of thermal expansion of bimetal materials, m is the ratio of the thickness of the individual layers of the bimetal, and n is the ratio of the young modulus of the individual layers of the bimetal [8].

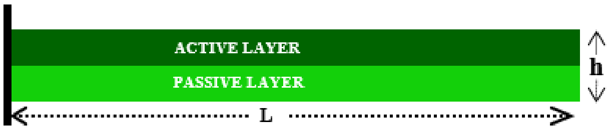


Fig. 2. Fixed-free support bimetallic beam

Different scientists and researchers used bimetals in capacitors. The gap produced between the layers of capacitors due to the thermal deflection of bimetals can be used for auto-tuning of the capacitance of capacitors [9, 10]. In 1993, W. H. Chu *et al* proposed a model relating the tip deflection of bimetallic cantilever microactuator with temperature change. The results of the model were compared with Finite Element Analysis results. The presented model produced results with accuracy better than 10% [11]. In 2011, M. A. Ismail et al. used Fiber Bragg Grating (FBG) Bimetalas a temperature sensor to measure the temperature of solar panels. This (FBG) bimetal temperature sensor has maximum sensitivity between 41 to 90°C[12].In 2012, A. V. Rao et al. used Finite Element Analysis to develop an empirical formula to calculate the thermal deformation of a bimetallic beam under the change in temperature. The results concluded that thermal deformation of the bimetallic beam is linearly related to change in temperature[13]. In 2020, Z. Zhang et al. used bimetal to steer the configuration of solar panels. The bimetallic effect is used to steer solar panels in such a direction so that solar cells get maximum solar radiation[14].In 2020, M. Kang et al. used free end and fixed-fixed support bimetal beams for the thermal energy harvesting based on combined piezo and pyroelectric effect. This work used small temperature variations with a frequency below 0.1 Hz. The prototype produces a power output of about 0.4 µW at a temperature difference of 15 K [15]. In 2021, R. K. Jaya Kumar et al. compared the electro-thermal deflection between Copper-Steel and Aluminium-Steel bimetals composites by using ANSYS. This simulation used the current ranges between 1-32 Amperes. Results concluded that Aluminium-Steel showed more deflection than Copper-Steel bimetal composites [16].In 2021, M. Talha Khan used ANSYS Static Structural to compare the thermal deformation between copper-steel and Aluminium-Steel bimetals. This simulation compared the thermal deformation in bimetals against a temperature range of 22 to 300 °C. At maximum temperature of 300 °C, Copper-Steel showed a thermal deformation of 0.36 mm and Aluminium-Steel showed thermal deformation of 0.62 mm [17]. Different scientists and researchers studied the thermal behavior of bimetals and used them in different engineering fields and technology [18-30]. Many scientists have used ANSYS and Fuzzy for their research work for better results [31-42].

2. FUZZY LOGIC CONTROLLER SIMULATION

Fuzzy Logic Controller (FLC) is an innovative simulation technique provided by MATLAB. FLC is used to deal with problems in the shade of grey. In this work, Tip Deflection Fuzzy Logic Controller (TDFLC) is designed to observe the tip deflection of a copper-steel bimetallic strip. The TDFLC consists of three input variables as T.Diff, Thickness, and Length while TDeflection is the output variable. The Fuzzy Inference System (FIS) of TDFLC using the Mamdani model is depicted in the figure.

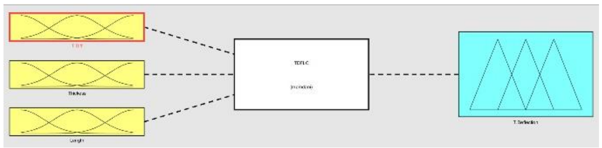


Fig. 3. TDFLC Function Designer

Three membership functions are designed for each TDFLC variable using the membership function editor. The membership functions of T.diff consist of smallT, medium, and highT. The membership functions of Thickness consist of the thick, medium, and thin. The membership functions of Length consist of small, medium, and largeL. The membership functions of output variable TDeflection consist of smallT.D, mediumT.D, and largeT.D. The membership functions of input variables T.diff, Thickness and Length, and output graph of T.D are depicted in Figures 4-7.

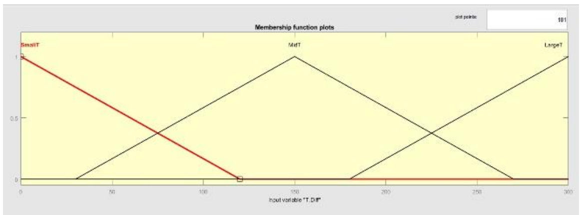


Fig. 4. Membership Function for T.Diff variable

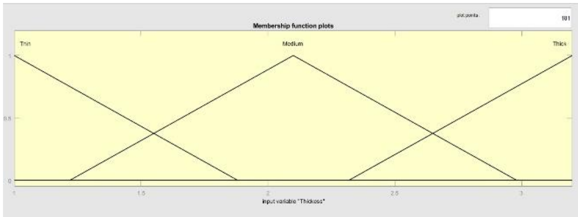


Fig. 5. Membership Function for Thickness variable

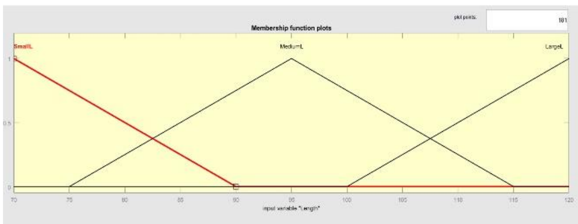


Fig. 6. Membership Function for Length variable

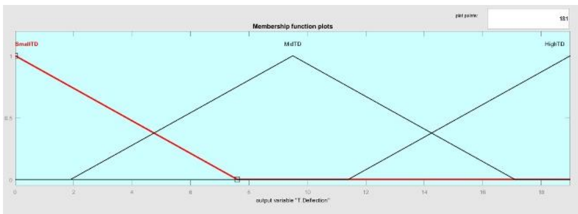


Fig. 7. Membership Function for T.Deflection variable

TDFLC has three input variables and corresponding three membership functions for each input variable. To observe tip deflection 27 rules are defined using IF-AND-THEN logic in the TDFLC rule editor according to the following equation

$$\text{Number of rules} = m^n$$

Where m and n represent the membership function and number of input variables. Rules for TDFLC are shown in table 1.

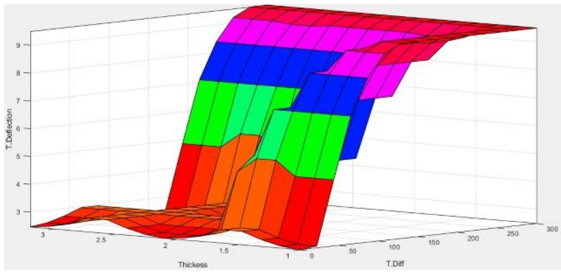
Table 1. Rules for TDFLC

No.	T.Diff (°C)	Thickness (mm)	Length (mm)	T.Deflection (°C)
1	SmallT	Thin	SmallL	SmallTD
2	SmallT	Thin	MediumL	SmallTD
3	SmallT	Thin	LargeL	SmallTD
4	SmallT	Medium	SmallL	SmallTD
5	SmallT	Medium	MediumL	SmallTD
6	SmallT	Medium	LargeL	SmallTD
7	SmallT	Thick	SmallL	SmallTD
8	SmallT	Thick	MediumL	SmallTD
9	SmallT	Thick	LargeL	SmallTD
10	MidT	Thin	SmallL	SmallTD
11	MidT	Thin	MediumL	MidTD
12	MidT	Thin	LargeL	MidTD
13	MidT	Medium	SmallL	SmallTD
14	MidT	Medium	MediumL	SmallTD
15	MidT	Medium	LargeL	MidTD
16	MidT	Thick	SmallL	SmallTD
17	MidT	Thick	MediumL	SmallTD
18	MidT	Thick	LargeL	SmallTD
19	LargeT	Thin	SmallL	MidTD
20	LargeT	Thin	MediumL	MidTD
21	LargeT	Thin	LargeL	HighTD
22	LargeT	Medium	SmallL	SmallTD
23	LargeT	Medium	MediumL	MidTD
24	LargeT	Medium	LargeL	MidTD
25	LargeT	Thick	SmallL	SmallTD
26	LargeT	Thick	MediumL	MidTD
27	LargeT	Thick	LargeL	MidTD

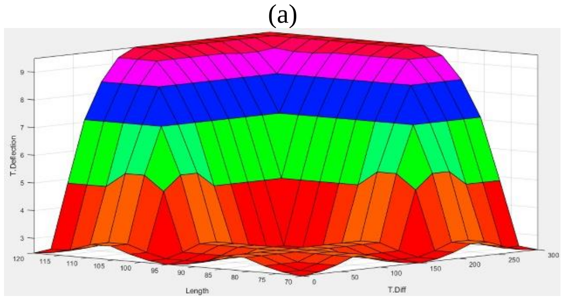
Based on designed membership functions and defined rules TDFLC generates output results for tip deflection. TDFLC Rule viewer shows a crisp value of T.Deflection for specified values of input. For a crisp value of T.Diff to be 278 °C, Thickness to be 1.4 mm and Length to be 120 mm TDFLC generate a crisp value of 12.8 mm for T.Deflection as depicted in the figure

Fig. 8. Rule Viewer TDFLC

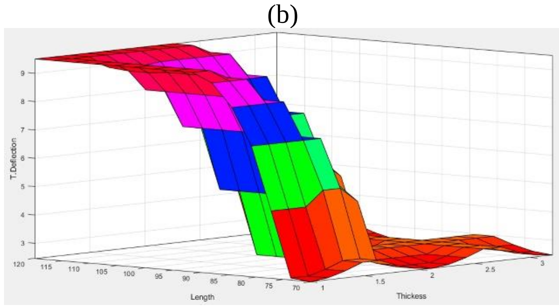
The 3-D surface viewer graph with input variables T.Diff, Thickness, and Length and output variable T.D is depicted in fig 9. Fig 9a presents the dependency of T.Deflection on T.Diff and Thickness. Fig 9b presents the dependency of T.D on T.Diff and Length. Fig 9c presents the dependency of T.D on Thickness and Length. The TDFLC surface viewer with input variables along x and y-axis while output along the z-axis is depicted in fig



(a)



(b)



(c)

Fig. 9. 3-D Surface Viewer TDFLC for T.Deflection. Fig. 9a. presents the dependency of T.Deflection on T.Diff and Thickness. Fig. 9b. presents the dependency of T.D on T.Diff and Length. Fig. 9c. presents the dependency of T.D on Thickness and Length.

3. ANSYS SIMULATION

ANSYS is a very powerful software for real-time simulations. ANSYS is very popular around the world for multiphysics simulations. In this study, ANSYS Static Structural is used to observe the tip deflection in a Copper-Steel bimetallic strip. The geometry of the bimetallic strip with dimensions of 120×7×1.4 mm is designed in ANSYS Workbench design modeler as depicted in figure

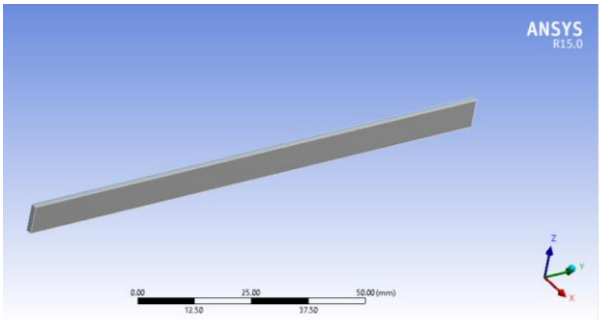


Fig. 10. Modeling of Bimetallic strip

The initial temperature of the bimetallic beam is 22 °C. For real-time simulation, material properties are selected by ANSYS Engineering data source. The material properties with dimensions of an individual layer of the bimetallic strip are shown in table 2.

Table 2. Material Properties of bimetallic Strip

Parameters	**Material**	
	Steel	**Copper**
Length (mm)	120	120
Width (mm)	7	7
Thickness (mm)	0.7	0.7
Initial Temperature (°C)	22	22
Density (kgm^{-1})	7850 [16]	8300 [16]
Young Modulus (Pa)	2E+11 [16]	1.1E+11 [16]
Poisson's Ratio	0.3 [16]	0.34 [16]
Bulk Modulus (Pa)	1.6667E+11 [16]	1.1458E+11 [16]
Shear Modulus (Pa)	7.6923E+10 [16]	4.1045E+10 [16]
Coefficient of Thermal expansion ($°C^{-1}$)	1.2E-05 [16]	1.8E-05 [16]

For precise simulation, the bimetallic strip geometry has finely meshed with the size of elements set to be 0.7 mm. The meshed setting comprises medium smoothing, coarse relevance center, and coarse span angle center. The meshed geometry is composed of 25906 nodes and 3440 elements in total.

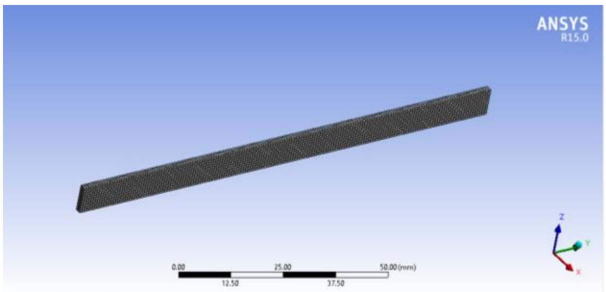
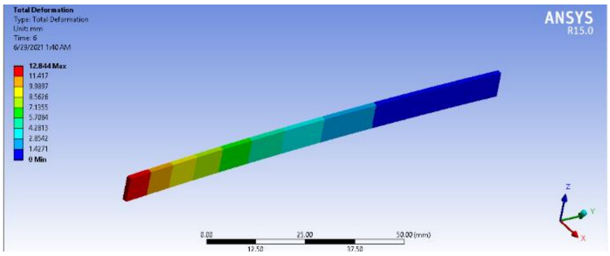


Fig. 11. Meshing of Bimetallic Strip

The thermal condition of 300 °C is applied on Copper-Steel bimetallic strip to observe the thermal deflection on its tip. The initial temperature of the bimetallic strip is 22 °C with zero tip deflection. When temperature increase, bimetallic strip experience thermal deflection on the tip side of the strip. At 300 °C temperature, the bimetallic strip shows a tip deflection of 12.8 mm as depicted in figure 12.

Fig. 12. Tip Deflection in Copper-Steel bimetallic Strip

4. RESULTS AND DISCUSSION



For Fuzzy simulation, Tip Deflection Fuzzy Logic Controller (TDFLC) is designed with three input variables as T.Diff, Thickness, and Length and T.Deflection as output variable. TDFLC Rule Viewer is used to observe the T.Deflection for crisp values of inputs. For a crisp value of T.Diff to be 278 °C, Thickness to be 1.4 mm, and Length to be 120 mm TDFLC generates a crisp value of 12.8 mm for T.Deflection. For real-time simulation, a geometry of Copper-Steel bimetallic strip with dimensions of 120×7×1.4 mm is designed by ANSYS Static Structural. The initial temperature of the bimetallic strip is 22 °C. At 300 °C temperature, the bimetallic strip shows 0 mm deflection at the fixed support end-side while a thermal deflection of 12.8 mm at the free end side of the bimetallic strip. Both Fuzzy Logic and ANSYS Static Structural show the same tip deflection of 12.8 mm for a temperature difference of 278 °C. For verification of simulations results, tip deflection is also calculated using the standard formulation of thermal deflection for a fixed-free support bimetallic beam. For Copper-Steel bimetal, using the specific deflection is 4.4×10^{-6} $°C^{-1}$ calculated by equation 2. For a temperature difference of 278 °C, length of 120 mm, and thickness of 1.4 mm using equation 1 the tip deflection comes out to be 12.6 mm. When the results of these simulations are compared with standard formulation results of tip deflection of bimetal both simulations show an error of 1.59%; The simulation's results are in good agreement with the standard formulation results. The results of the work concluded that the tip deflection for fixed free bimetallic strips is inversely related to thickness while in direct relation with both Temperature difference and Length of bimetal. Results are shown below in table 3.

Table 3. Comparison of Results for Tip Deflection

Categories	**Tip Deflection**
Formulation (mm)	12.6
Simulation (mm)	12.8
ANSYS Static Structural	12.8
Error (mm)	0.2
% Error	1.59

5. CONCLUSION

The purpose of this work is to simulate the tip deflection of a fixed free support Copper-Steel bimetallic strip using Fuzzy Logic Controller and ANSYS Static Structural. Simulation software is used to observe the dependency of tip deflection on temperature difference, thickness, and length of bimetallic strips. For a crisp value of temperature difference of 278 °C, the thickness of 1.4 mm and length of 120 mm TDFLC generates a tip deflection of 12.8 mm. For the same input conditions, ANSYS Static Structural also observe the same tip deflection of 12.8 mm. In the comparison of results with standard formulation of tip deflection, both TDDLC and ANSYS generate results with a % error of 1.59 %. These simulations concluded that the tip deflection for fixed free bimetallic strips is inversely related to thickness while in direct relation with both Temperature difference and Length of bimetal.

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