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Full Length Research Paper

A Fuzzy Logic Based Model to Predict the Fretting Fatigue Life of Aerospace Al7075-T6 Alloy

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Fretting fatigue is a phenomenon which occurs when two parts are contacted to each other and one of those parts or both are subjected to cyclic load. Fretting decreases fatigue life of materials drastically. Therefore Investigation of fretting fatigue life of materials is an important subject. In this work the fretting fatigue life of AL7075-T6 alloy has been investigated by conducting a series of rotary bending fatigue tests at 50 Hz. A fuzzy logic model was offered to predict the fretting fatigue life of AL7075-T6 with respect to changes in input process parameters, friction pads pressure and bending stress amplitude. Two membership functions are allocated to be connected with each input of the model. The predicted results achieved via fuzzy logic model were compared to the experimental result. The result demonstrated an arrangement between the fuzzy model and experimental results with the 94.72% accuracy.

Key words: Fretting fatigue, AL7075-T6 alloy, fuzzy logic model

1. INTRODUCTION

Fretting is the surface damage that occurs when contacting surfaces between mating bodies experience an oscillatory motion of small amplitude. When fretting occurs under fluctuating loading condition, the process is termed fretting fatigue. Fretting fatigue increases the tensile and shear stresses at the contact surface producing surface defects which can act as stress concentration sites (Sadeler et al., 2009). Fretting fatigue is a common occurrence in multitude of components or structures involving riveted joints, bolted joints, wire ropes, and dovetail joints of gas turbine engine (Majzoobi and Jaleh, 2007). Fretting is decreased fatigue life of materials drastically. When fretting is applied on the surface of materials, the stress concentration at fretting region is increased and micro crack appears and starts to grow. Cracks may assert in some cases, while in others they may propagated, eventually causing failure. Regions such as in the dovetail joint in a turbine engine, where the blade and disk are in contact and undergo vibratory stresses, are especially susceptible to fretting fatigue and have been subject of studies for a number of years (Majzoobi and Jaleh, 2007).

Aluminum alloy, which has superior mechanical properties, low cost, light weight and reliability, has been widely used for aircraft engines, fuselage, and automobile parts. Aluminum 7075-T6 alloy which is used in this research work has low specific weight and high strength to weight ratio and also high electrical and thermal conductance. This alloy is widely used in industry and in particular in aircraft structure and pressure vessels, however, it is always subject to different working conditions. Wear and fretting normally begin when the substrate is in contacting with other surfaces and rubbing each other under normal load, causing shear force to act on the surface (Majzoobi and Jaleh, 2007).

To investigate the fretting fatigue life of AL7075-T6, it requires predicting the fretting fatigue life of specimen at different conditions. Hence, a reliable systematic approach is thus required (Chandrasekaran et al., 2009). Soft computing techniques are useful when exact mathematical information is not available. The techniques differ from conventional computing in that it is tolerant of imprecision, uncertainty, partial truth, approximation, and met heuristics (Shamshirband et al., 2010). Fuzzy logic is one of the soft computing techniques that play an

important role in input-output parameter relationship modeling. The fuzzy modeling technique is used when subjective knowledge and suggestion by the expert are significant in defining objective function and decision variables. Fuzzy logic is preferred in predicting fretting fatigue life performance based on the input variables due to nonlinear condition in fretting fatigue process (Shamshirband et al., 2010). In this work, fuzzy logic is used to develop the rule model in order to predict the fretting fatigue life of AL7075-T6 based on parameters interaction.

2. DESIGN OF EXPERIMENTS

The most important stage in the design of an experiment lies in the selection of parameters and identifying the experimental array. In this experiment with two parameters and four levels each, the fractional factors design used is L_9 experimental array. This array is chosen due to its capability to check the interactions among parameters. The parameters and levels are assigned as in Table 1. The eighth experiments with the details of combination of the experimental levels for each parameter (A and B) are shown in Table 2.

Table 1. Parameters and levels used in the experiment

	Control factors	Experimental condition levels			
		1	2	3	4
A	Fretting force (MPa)	50	75	100	125
B	Stress amplitude (MPa)	150	200	250	300

Table 2. Standard experimental array

Experiment	Parameters combination	
	A	B
1	1	1
2	2	2
3	3	3
4	4	4
5	1	2
6	2	1
7	1	3
8	3	2
9	4	3

3. EXPERIMENTAL DETAILS

3.1. Specimen's material and geometry

Aluminum 7075-T6 alloy was used in this investigation. From a number of tensile tests, the yield stress and ultimate strength of Al7075-T6 were obtained as: **σ_y=520MPa and σ_{ut}=590 MPa,** respectively. Fretting fatigue test specimens were machined with initial surface roughness R_a=0.6±0.1µm by lathe turning (CNC Lathe Machine, Miyano, BNC-42C5). The round shape specimens used in this work, were prepared in accordance with ISO standard (Norton, 2010). The drawing and dimension of fretting fatigue specimen is illustrated in Fig. 1.

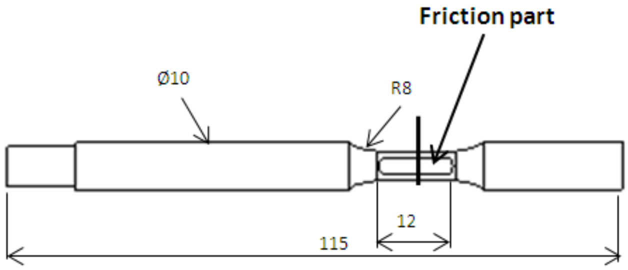


Fig. 1: Drawings of the fretting fatigue specimen

3.2. Fretting fatigue testing

The specimens were gripped and loaded rotationally in a rotating bending fretting fatigue testing apparatus. By adjusting the load screw on a proving ring with a torque driver, the normal contact load between the contact pads and specimen was controlled. The fretting fatigue tests were carried out at different contact pressure. When a fatigue specimen is subjected to cyclic stresses, fretting between the contact pads and specimen is generated. Plain and fretting fatigue testing were carried out at room temperature in a two- point loading rotating bending machine (R=-1) under constant stress amplitude at a rotational speed of 3000 rpm. The nominal maximum cyclic stress was set at value that was expected to result in a fatigue life of between 10^4 and 10^7 cycles and test were stopped if the specimen did not fail at 1×10^7 cycles.

Fretting fatigue pads were fabricated from AISI 4140 steel plate that has hardness of 346 HV. Substrate material (179HV) is softer than the pads. A ring type load cell and bridge-type fretting pads was designed and manufactured, which can simulate fretting fatigue conditions. Figure 2 shows a schematic view of fretting fatigue test setup and drawing of friction pads employed in this present study.

The friction force, created by normal force and sliding movement between the specimen and pads and the friction coefficient is measured by a friction test machine. The amount of friction coefficient between pads (AISI 4140 steel) and AL7075-T6 was calculated to be around 0.607. The friction force can be determined from the relation $F=\mu.P$ in which P is the contact load calculated by ring shape load cell (Fig. 2) and F is the friction force measured from the friction test machine.

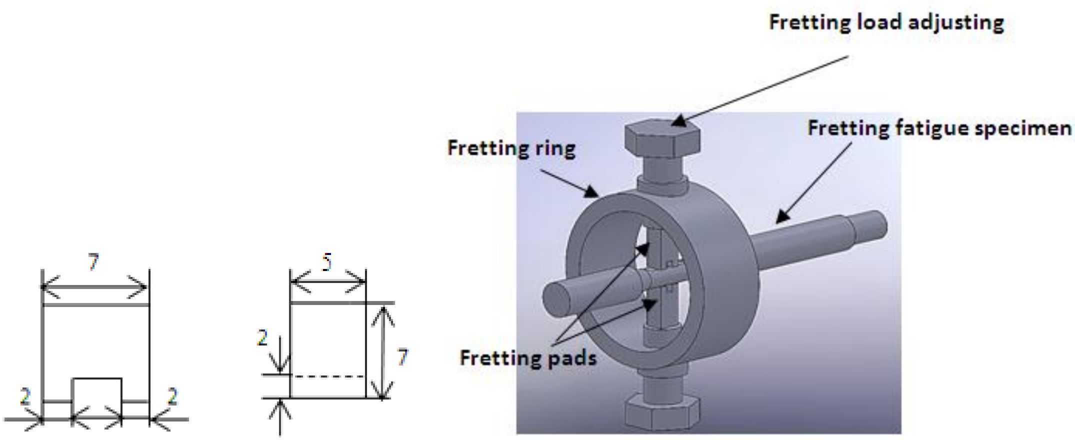


Fig. 2: Schematic of fretting fatigue test rig

4. EXPERIMENTAL RESULT

In order to investigate the plain fatigue life of AL7075-T6 alloy some experiments were carried out and the results are shown in Fig. 3. The experiments were conducted for stress ratio of R=-1, 50 Hz at different contact pressure from 50 to 125MPa and working stress amplitudes of 150 to 300MPa. The relationship between the stress amplitude and the number of cycles to failure for all the condition analyzed is defined by equation 1 (Shahzad et al., 2010).

$$S= AN_f^b \qquad (1)$$

where, S is Stress amplitude, A is Fatigue strength coefficient, b is Fatigue strength exponent, and N_f is Number of cycles to failure. *S*-N curve was obtained by least square fitting relationship in Equation 1 (Shahzad et al., 2010). Figure 3 shows the number of cycle to failure versus stress for plain fatigue specimens under the S/N curve while; the fretting fatigue lives of specimens at different parameters condition are summarized in Table 3 and shown in Fig. 4.

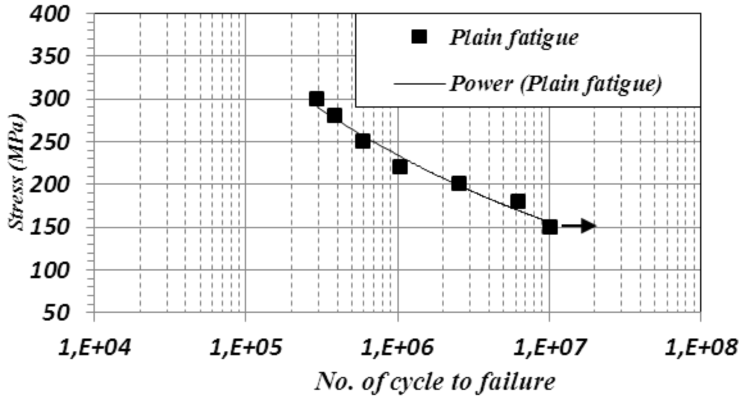


Fig. 3: S/N curve of plain fatigue for AL7075-T6

Table 3: Fretting fatigue life

Experiment	Average cycle to failure
1	9887647
2	3547157
3	473618
4	77869
5	3946351
6	7963421
7	663498
8	2443214
9	201156

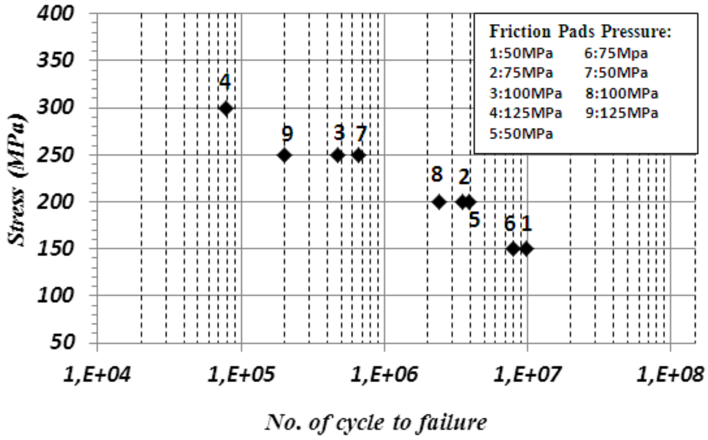
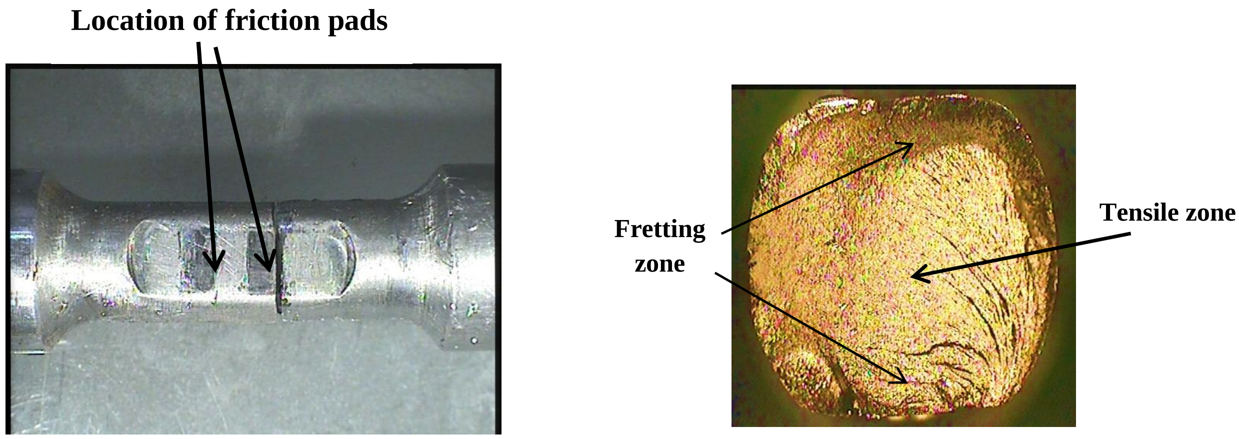


Fig. 4: S/N curve of fretting fatigue test accompany to their number of test and friction pads pressure

Fracture surfaces of tested specimens after 2.4×10^{6} cycles at 200MPa were examined using optical microscopy. Typical result fractured surface and cross section of specimen are illustrated in Fig. 5. The figure clearly indicates that the fracture surface consists of two quite distinct regions; a fatigue zone created by crack propagation and a tensile region which gives rise to fracture of specimen when it is sufficiently weakened by the crack zone development. If the failed surface is viewed at higher magnification, the striations due to each stress cycle can be seen as in Figure 5 (b), which shows the crack surface of a failed aluminum 7075-T6 at 40 ×

magnification along with a representation of the stress-cycle pattern that failed it. The occasional large-amplitude stress cycles show up as larger striations than the more frequent small-amplitude once, indicating that higher stress amplitudes cause larger crack growth per cycle (Shahzad et al., 2010). Figure 6 shows the SEM micrograph of specimen after fracture at stress of 220MPa and friction pad pressure where the cracks and fracture under friction pads were clearly observed.



(a) Fracture in AL7075-T6 specimen

(b) Cross-section view of specimen under fretting fatigue

Fig. 5: Fracture surface and cross-section view of specimens under fretting fatigue after 2.4,E+06 cycles at 200MPa stress

5. FUZZY LOGIC BASED MODEL TO PREDICT FRETTING FATIGUE LIFE

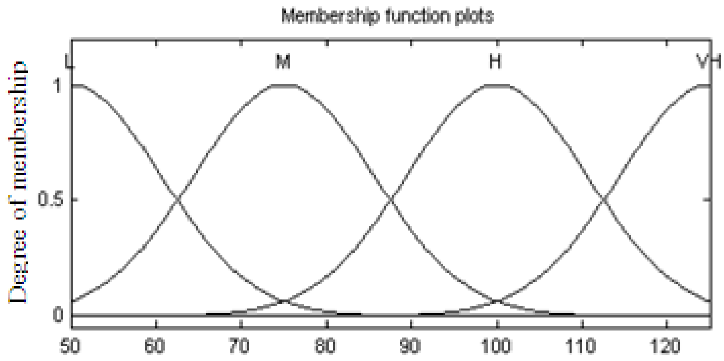
The relationship between input parameters which are friction pads pressure and stress with the output parameter which is fretting fatigue life of AL7075-T6 were referred to construct the rules. Fuzzy linguistic variables and fuzzy expression for input and output parameters are shown in Table 4. For each variable, four membership functions were used which are Low, Medium, High, and Very High for inputs. The output variable (fretting fatigue life) also used four membership function, ranging from Bad, Average, Good, and Excellent. The characteristics of the Inputs and Output variables are shown in Table 4.

Table 4: Fuzzy linguistic and abbreviation of variables for each parameter

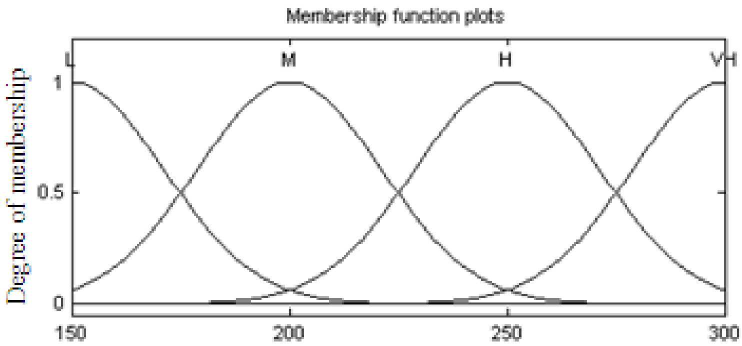
	Inputs	Range
Parameters	Linguistic variables	
A- Friction pads pressure MPa B- Bending stress MPa	Low (L), medium (M), high (H), very high (VH)	50-125 150-300
	Output	
Fretting fatigue life	Bad, Average, Good, Excellent	77869-9887647

5.1. Membership functions for input and output fuzzy variables

In choosing the membership functions for fuzzification, the event and type of membership functions are mainly dependent upon the relevant event. In this model, each input and output parameter has four membership functions. Gauss shape of membership function was employed to describe the fuzzy sets for input variables. In output variables fuzzy set, triangular shape of membership functions are used. Triangular membership function is generally used and has gradually increasing and decreasing characteristics with only one definite value (Jaya et al., 2010).The input variables have been partitioned according to the experiment parameter ranges. Membership functions for fuzzy set input, friction pads pressure and bending stress variable, are shown in Figs.7 (a) and (b) respectively. Membership functions for fretting fatigue life fuzzy set is shown in Fig.8.

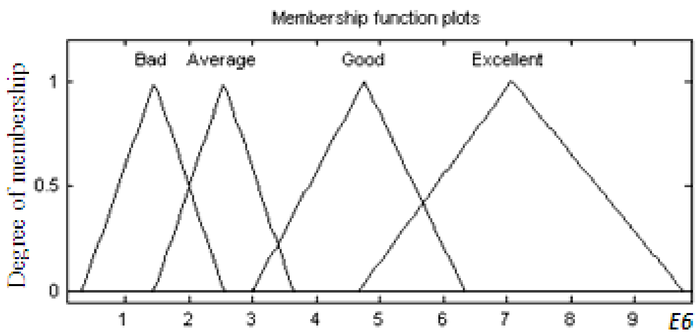


(a) Input variable (friction pads pressure MPa)



(a) Input variable (bending stress MPa)

Fig. 6: Membership function for inputs



Output variable (fretting fatigue life)

Fig. 7: Membership function for output

5.2. Structure of fuzzy rules

A set of 9 rules have been constructed based on the actual experiment of fretting fatigue life of AL7075-T6. Experimental results were simulated in the Matlab software on the basis of Mamdani Fuzzy Logic as follow:

1. IF (A is L) and (B is L) then (Fretting Fatigue life is Excellent)
2. IF (A is M) and (B is M) then (Fretting Fatigue life is Good)
3. IF (A is H) and (B is H) then (Fretting Fatigue life is Average)
4. IF (A is VH) and (B is VH) then (Fretting Fatigue life is Bad)
5. IF (A is L) and (B is M) then (Fretting Fatigue life is Good)
6. IF (A is M) and (B is L) then (Fretting Fatigue life is Excellent)
7. IF (A is L) and (B is H) then (Fretting Fatigue life is Average)
8. IF (A is H) and (B is M) then (Fretting Fatigue life is Good)
9. IF (A is VH) and (B is H) then (Fretting Fatigue life is Bad)

Table 5: The accuracy and error of the fuzzy logic model

No. of Exp	Parameters (Inputs)		Fretting fatigue life (output)		Error %	Accuracy %
			Measured fretting fatigue life	Fuzzy predicted fretting fatigue life		
	A	B	Average			
1	60	180	7546321	7931184	5.10	94.90
2	90	220	2154369	2255625	4.70	95.30
3	110	275	124637	132165	6.04	93.96
				Accuracy of Model =	94.72	

5.3. Defuzzification

Defuzzification is the conversion of a fuzzy quantity to a precise value, just as fuzzification is the conversion of a precise value to a fuzzy quantity (Leung et al., 2003). Seven methods are available in literatures to be used by researchers for defuzzifying methods: centroid, weight average, mean of max, center of sum, center of largest area, first (or last) of maximum method. The selection of the method is important and it greatly influences the speed and accuracy of the model. In this model, centroid of area (COA) defuzzification method is used due to wide acceptance and capability in giving more accurate result compared to the others (Oktem and Hasmi, 2006).

Figure 9 is example to demonstrate the effect of parameters change on fretting fatigue life of AL7075-T6 predicted by fuzzy based model. As it can be seen from Fig. 9 with increasing the bending stress from 150 to 300MPa, the fretting fatigue life of specimens is decreased. Friction pads pressure has no effect on fretting fatigue life of specimens from 50 to 75MPa, while with more increase of pressure; the fretting fatigue life is decreased significantly. The proposed fuzzy logic model gives promising solution to predict fretting fatigue life value in the specific range of parameters.

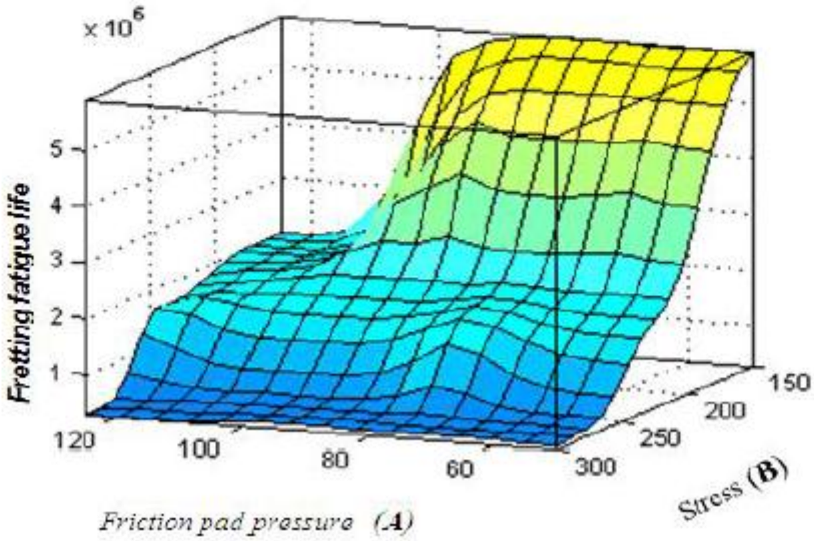


Fig. 9: The surface hardness obtained by fuzzy logic in relation to parameters change

6. INVESTIGATE THE FUZZY MODEL ACCURACY AND ERROR

After the fuzzy rules were constructed, other new three experimental tests from separated experiment were carried out while the proposed fuzzy model is used to predict the fretting fatigue life at the same conditions as shown in Table 5. Figure 10 shows the comparison between fuzzy logic model prediction and the experimental results. The close assent of fretting fatigue life values of AL7075-T6 obviously display that fuzzy logic model can be used to predict fretting fatigue life of AL7075-T6 parameters under consideration to investigating the fuzzy model accuracy and error. The individual error percentage was obtained by dividing the absolute difference of the predicted and measured values by the measured value as shown in Equation (2) where e_i is individual error, F_m is measured fretting fatigue value and F_p is predicted value.

$$e_i = \left(\frac{|F_m - F_p|}{F_m}\right) \times 100\% \qquad (2)$$

Meanwhile, accuracy was calculated to measure the closeness of the predicted value to the measured value. The model accuracy was the average of individual accuracy as shown in Equation (3) where A is the model accuracy and N is the total number of data set tested.

$$A = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{|F_m - F_p|}{F_m}\right) \times 100\% \qquad (3)$$

Figure 11 (a) and (b) shows the fuzzy model accuracy and error percentage. The highest percentage of error for fuzzy model prediction is 6.04%. The fuzzy model accuracy is 94.72%. The low level of errors shows that the fuzzy predicted fretting fatigue life results were very close with actual experimental fretting fatigue life values. The value of accuracy shows that the proposed model can predict the fretting fatigue life of AL7075-T6.

7. DISCUSSION

The selection of the fretting fatigue conditions is essential for fretting fatigue life of AL7075-T6 measurement. The most important parameters affecting the fretting fatigue life are the friction pad pressure and bending stress.

From the experimental analysis and the fuzzy model prediction results shown in Fig. 9 the fretting fatigue life of specimens is decreased with increasing friction pads pressure from 75 to 125MPa, while below this amount, the friction pads pressure has no significant effect on fretting fatigue life of AL7075-T6 at constant bending stress.

The bending stress also plays important roles in fretting fatigue life of specimen. Figure 9 indicates that, with increasing stress from 150 to 300MPa the fretting fatigue life of specimens are decreased, which is attributed to stress concentration under friction pads as observed in Fig.5. It is apparent that fretting has a deleterious effect on the fretting fatigue life of AL7075-T6 at all values of the applied bending stress (Araujo and Nowell, 2002).

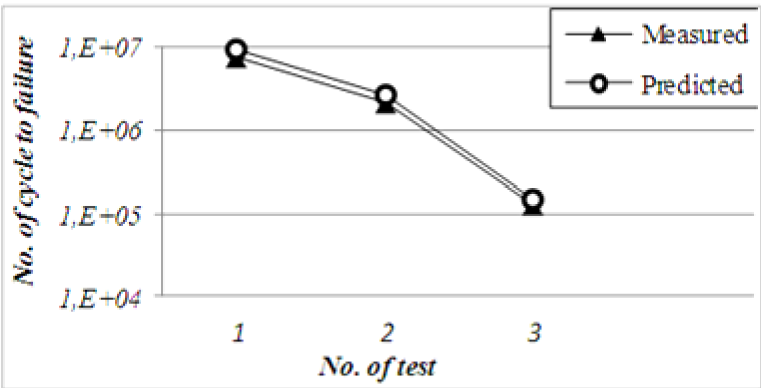
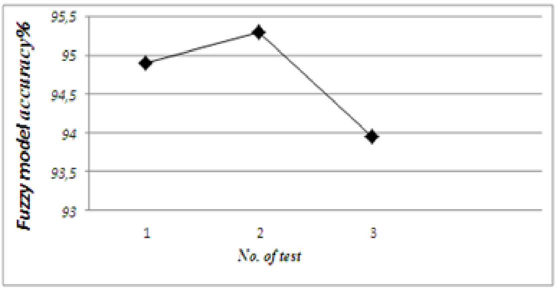
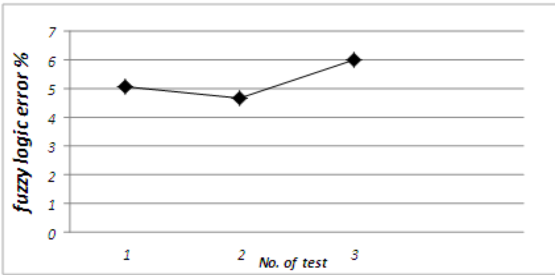


Fig. 10: comparison of fuzzy logic model prediction with the experimental results



(a) The fuzzy model accuracy percentage



(b) The fuzzy model error percentage

Fig. 11: The accuracy and error percentage of experimental result and fuzzy model prediction

It is observed that a fretting fatigue crack forms at the region where the frictional shear stress on contact surface locally concentrates. Thus, the decrease in fatigue life by the fretting damage is considered to be due to the increase in crack initiation caused by the local stress concentration caused by fretting, and the acceleration of the initial crack propagation by fretting (Jin and Mall, 2004)

The action of fretting causes considerable damage to the specimen surface. Figure 5 (a) shows the appearance of the fretting scars on specimens. It is clear that during plain fatigue, cracks originate randomly at one or several points around the periphery of the specimen case while during fretting, cracks inevitably start from the same location at point adjacent the leading edge of the fretting areas where the bending stress and the induced shear stress were highest (Lin et al., 2001) and (Mugadu et al., 2002). Crack propagation occurs from two sides resulting in the appearance of a final fracture area of the specimen as shown in Figs. 5 (b).

8. CONCLUSION

In this research work, prediction of fretting fatigue life of AL7075-T6 alloy was investigated at different parameters condition using fuzzy logic technique. From the result of the fuzzy logic prediction model, the following conclusion can be derived:

1. Fretting decreases the fatigue life of AL7075-T6 alloy drastically. The deduction of the fatigue life is attributed to the introduction of shear stress on the surface though contact between the fretting pads and the substrate.
2. The fuzzy model percentages of error and accuracy were found to be 6.04% and 94.72% respectively. It is indicated that the fuzzy logic prediction model could be used to predict the fretting fatigue life of AL7075-T6 alloy in a very accurate manner.
3. The pressure of the friction pads has no effect on fatigue life of AL7075-T6 from 50 to 75MPa, while from 75 up to 125MPa; it has deleterious effect on fatigue life of specimens.

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