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The Estimation of Semi Elliptical Surface Cracks Advancement via Fuzzy Logic

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***Abstract*—**This paper presented the results of an experimental investigation into the axial fatigue behavior of a 5086 aluminum alloy which have several notch-aspect ratios a0/c0 and notch thickness ratio a/t with semi-elliptical surface cracks. Tests were conducted in la b air for stress levels of 50 % of their yield strength. Experiments were carried out for various notch to thickness ratios. Crack growth rates of test specimens both in surface and depth directions were determined by using die penetration method. Fuzzy Logic method was used to predict the deep direction crack growth because the dept of the crack is considerably difficult to measure.

***Keywords*—**Axial fatigue, Crack growth rate, surface crack, Al-Mg alloy.

I. INTRODUCTION

DIFFERENT parts of many structures and machines required for modern technology were produced from Al-Mg alloys in aircrafts, submarines and light combat vehicles because of superior features as like low density, good formability, good weldability and high corrosion resistance.

Surface cracks are considered the most common flaws in aircrafts, pressure vessels and piping systems. A surface crack may escape from detection in inspection of structural components. Under cyclic pressurization, the surface crack evolves into a through-thickness crack reducing the useful service life. Fatigue cracks may occur and suddenly, spread quickly and cause catastrophic failure [1-8]. It is possible to take measures when the crack growth behavior is known. To reduce failures, surface crack behavior in structural components has been extensively investigated. For such investigations, sizing both the crack depth and the surface length is a prime concern. However, the depth of the crack is considerably difficult to measure. To overcome this difficulty, various non-destructive techniques have been employed, including the alternating current potential drop techniques [9], alternating current field measurement [10], direct current potential drop [11], ultrasonic examine [12], X-ray examine [13] and dye penetration [14]. The crack depths can be determined by foregoing methods. Thus, crack growth rates in depth direction can be easily predicted.

The purpose of this study was to investigate fatigue life of a 5086 aluminum alloy with semi-elliptical surface crack. The crack surface direction and deep crack growth were obtained experimentally. Both the crack depth and the surface length is a prime concern. However, the depth of the crack is considerably difficult to measure. So Fuzzy logic method can be estimated the process of the progression of the depth.

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The crack length direction can be known. Crack growth rates in depth direction can be easily predicted. The the crack depth direction and predicted from Paris-Erdogan equations and in addition. The comparison validity of the results was shown in graphical forms. The predicting results were compared with the experimental results. Experimental results were compared by the results of Fuzzy Logic Method.

II. FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalued logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of FL. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalued logical systems.

What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution. Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in AI, what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanisms provided by the calculus of fuzzy rules [15].

A. *Why Fuzzy Logic Approach Was Preferred?*

Fuzzy logic, unlike traditional control technology, is able to work with the gray areas that are present in today's complex processes. Fuzzy Logic, is not fuzzy". It has the capability to deal with the imprecise or sometimes vague inputs of any process.

The fuzzy logic algorithm is firmly rooted in the mathematics of the traditional control function. It uses these algorithms to describe the system relationships and it also uses this high-level mathematics to describe subjective concepts in the terms that the new microprocessors can

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understand. While microprocessors can only deal with 0/1, TRUE/FALSE situations, a fuzzy logic algorithm uses all numbers between 0 and 1. Fuzzy logic does not require a “crisp”set, but instead fuzzy logic can understand the gray areas. Fuzzy logic now can understand the gray areas that will occur in any type of process. However, it must not be forgotten that fuzzy logic is not a panacea. In certain applications fuzzy logic can provide additional functionality and better performance, but the traditional control methods will often provide more than satisfactory control results [16].

III. Fatigue Test Specimens

Under general loading, the stress intensity factor depends on three basic modes of deformation (tension and in-and-out of plane shear). But here only tensile loading was applied and, therefore, only Mode I fracture occured.

The boundary correction factor, $F(a_0/t,\ a_0/c_0,\ \phi)$, is a_0 function of the crack depth a_0, crack length c_0, plate thickness t and the parametrical angle of the ellipse ϕ (Fig. 1). The length of the specimen L_0 was chosen large enough to have a negligible effect on stress intensity (L_0/c_0 >5) [17-18].

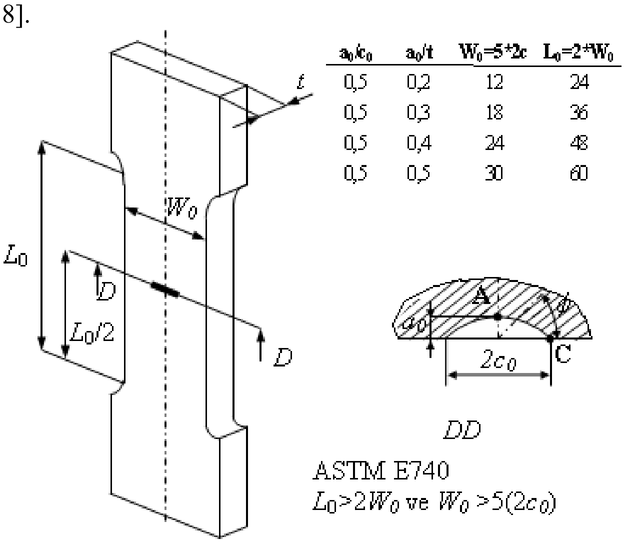


Fig. 1: The sketch of the axial fatigue test specimen geometry with semi-elliptical surface crack

IV. Experimental Study

Test specimens were prepared from stabilized and one quarter tempered (H32) 5086 Al-Mg alloy plates which are used for low density armour materials. The chemical composition of the material is given in Table 1.

In order to know the mechanical properties, tensile test specimens were taken from this alloy and prepared according to ASTM A 370 standard. Thickness of the specimens were chosen 3 mm in all tests. Tensile tests were performed by using Instron 150 LX tensile testing machine at room temperature with a 0.1 1/s strain rate and test results are given in Table 2.

Table I
Chemical Composition of 5086 Al-Mg Alloy

Si	Mn	Fe	Mg	Cr	Cu	Al
0.080	0.45	0.24	3.51	0.088	0.065	Rest

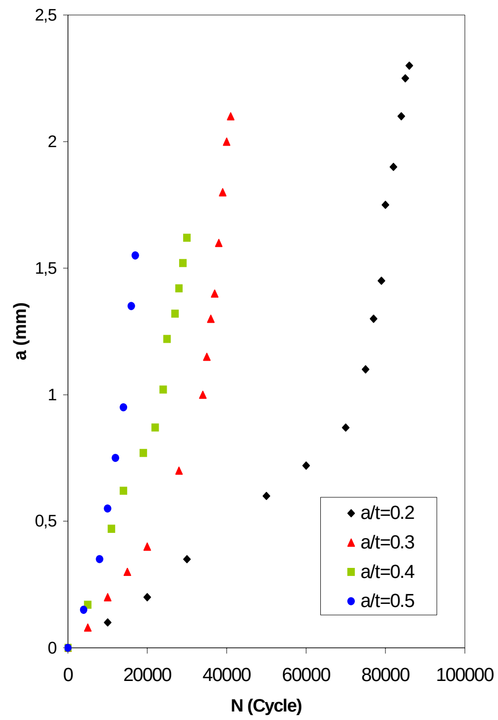
Table II
Mechanical Properties –of 5086 Al-Mg Alloy

Young’s modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
69	196	286	12

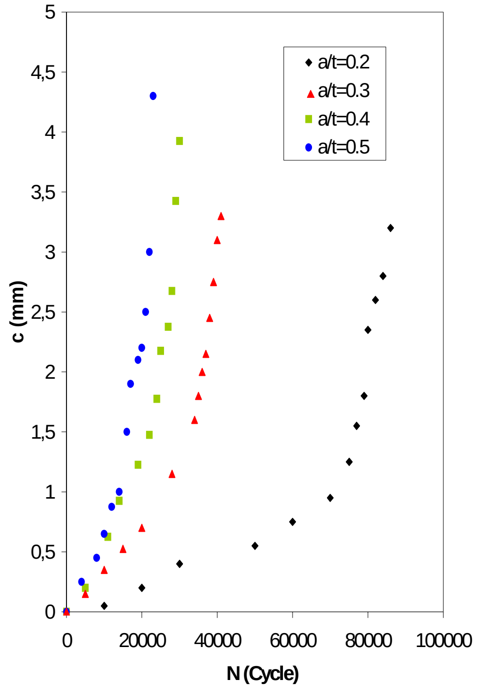
The surface cracked axial fatigue test specimens were machined according to ASTM-E 740 standard. In accordance with the aspect ratios a/c and crack depth ratios a/t, the width W and length L_o of the specimens were calculated. In the center of the specimens semi elliptical surface notches of a_o/c_o = 0.5 aspect ratio and a_o/t = 0.2, 0.3, 0.4 and 0.5 crack depth ratios were machined with an electro discharge machine (EDM) by using copper electrodes. Each specimen was pre-cracked by using a closed–loop servo hydraulic fatigue testing machine at room temperature. Fatigue tests were performed under constant amplitude with a sinusoidal waveform and a loading frequency of 12 Hz. The maximum stress σ_{max} was chosen one half of the yield strength of the material with the stress ratio (R= σ_{min} / σ_{max}) of 0.1. The surface length of the crack growth was measured with portable microscope with 40X. The crack depth growth was determined using dye penetration. Dye penetrations were applied in determined intervals of cycles related to a/c and a/t ratios. After testing the fracture surfaces were examined by an optical comparator with 0.005 mm precision. Crack depths were measured by assistance of color contour [19].

V. Result And Discussion

Crack length (2*c*) - *N* and crack depth (*a*) - *N* graphics were drawn. The variations of crack depth *a* and crack length *c* with the number of cycles *N* are shown in Fig. 2. The surface crack growth of the material occurred at the lower number of cycles. As shown in Fig. 2, the number of total cycles increases for lower a_0/t ratios.



(a)



(b)

Fig. 2: Crack lengths versus number of cycle for a/c=0.5 and a/t=0.2~0.5

(a) In depth direction (ϕ =90°), (b) In length direction (ϕ =0°)

The surface crack lengths are measured with portable microscope during the experiments. The crack depths are measured from the cracked surface by the optical comparator. Then crack growth rates of semi-elliptical surface cracks are calculated from measured lengths.

When examining the values used for Figs. 2.a and 2.b, it was seen easily that the crack growth rate was higher in the length direction than in the depth direction.

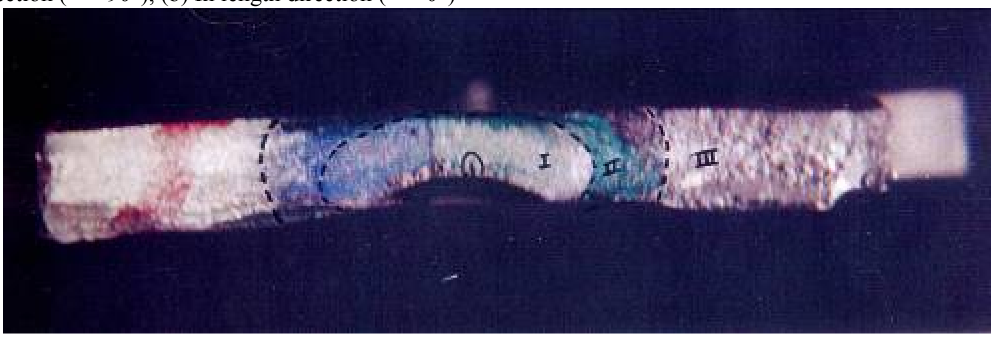


Fig. 3: Fractograph of the specimen of the surface cracks for a/c=0.5 and a/t=0.2

Figure 3 shows macro structure of specimen a_0/c_0=0.5 and a_0/t=0.2. When examining fracture surface, the crack grows in three basic geometric forms. In the first zone, the crack propagates by keeping its semi-elliptical form until it reaches the back surface. Compression stresses which developed during cold rolling process decrease the crack growth rate on the surface. This effect is seen clearly in Fig. 4 and it is dominant in shallow surface cracks (a_0/t=0.2 and 0.3). In the second zone, after reaching back surface the crack grows rapidly on both front and back surfaces, and crack becomes a through-thickness crack. In the third zone, static tensile rupture takes place.

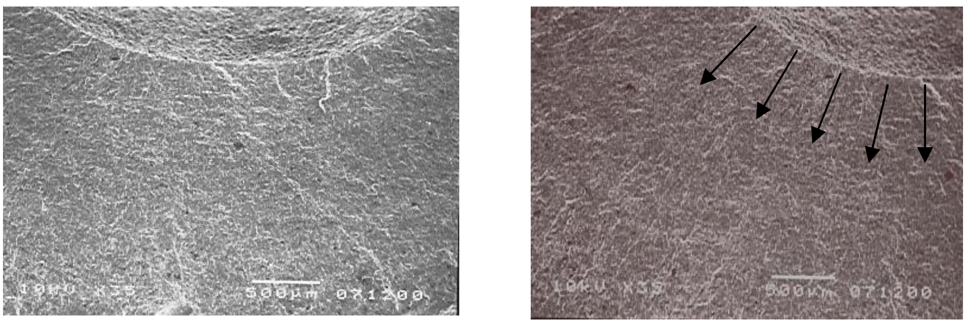


Fig. 4: SEM fractographs of the surface cracks for a/c=0.5 and a/t=0.2

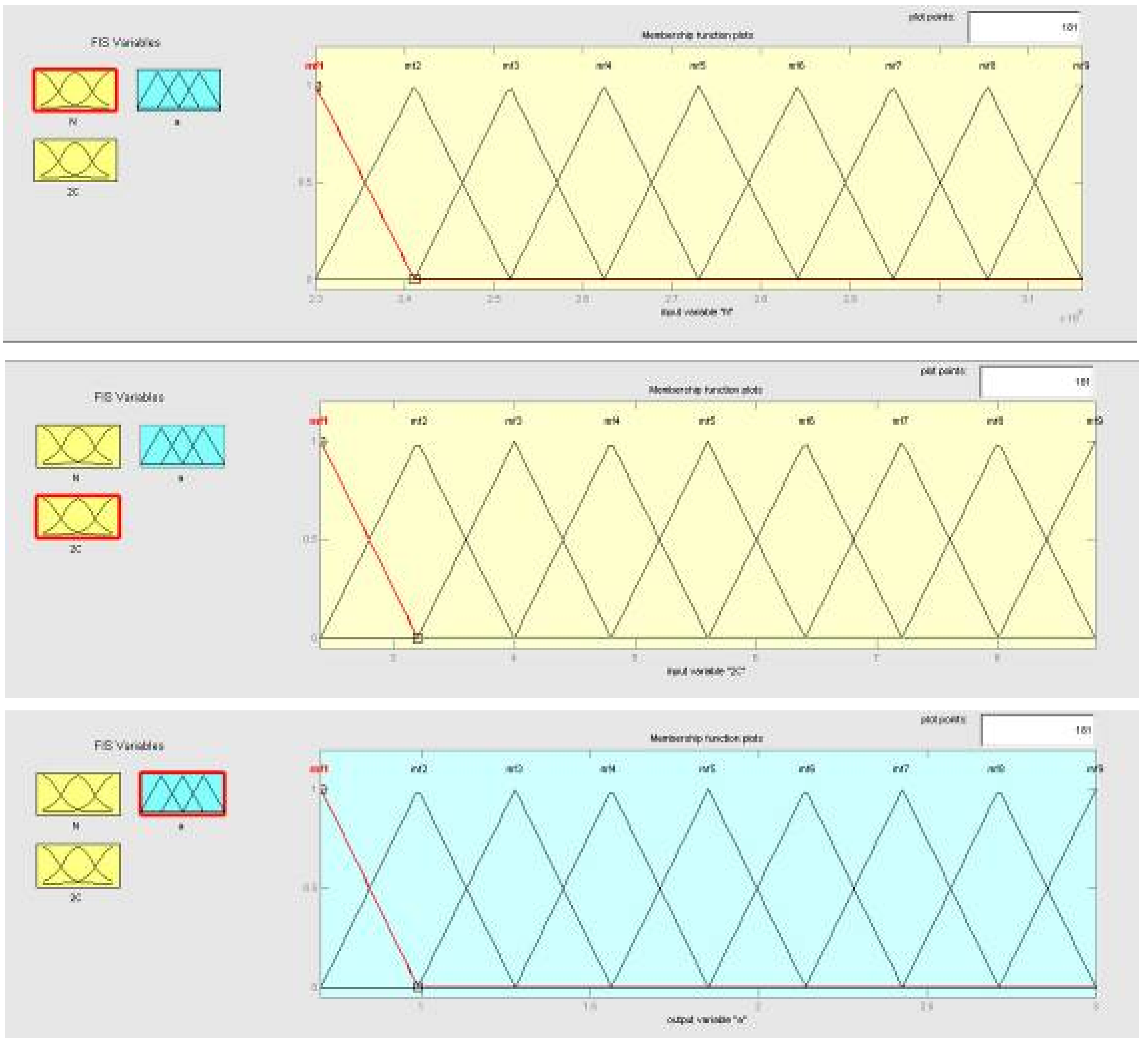
The appearance of the fatigue fracture surface is given in (Fig. 4). The crack grows approximately perpendicular to the crack profile (in parametric angle, ϕ direction).

A. Fuzzy Logic Crack Depth Predictions

a (mm) 's calculation of the fuzzy logic method is shown below. Designed fuzzy system input variables of N and 2c, a (mm) is the output variable. Linguistic expressions used here; mf1= extremely little, mf2=very very little, mf3= very little, mf4=little, mf5= less than medium, mf6=medium, mf7=more than medium, mf8= much, mf9=too much .

For the inference mechanism the Mamdani max-min inference was used. a/c = 0.5 and a/t = 0.2 sample shows the input and output variables. a/c = 0.5 and a/t = 0.3 - 0.4 - 0.5 in the above sample input and output linguistic variables are used [20].

a/c=0,5 and a/t=0,2			
N(cycle)	**2c(mm)**	**experimental**	**Fuzzy Logic prediction**
230000	2,40	0,70	**0.78**
240000	2,50	0,80	**0.85**
250000	2,80	1,00	**0.94**
260000	3,20	1,15	**1.12**
280000	3,50	1,30	**1.39**
290000	3,90	1,42	**1.42**
300000	4,30	1,57	**1.88**
305000	4,90	1,80	**1.90**
307000	5,50	2,00	**2.22**
309000	6,00	2,15	**2.39**
310000	7,10	2,45	**2.55**
312000	7,60	2,60	**2.59**
314000	8,00	2,80	**2.71**
316000	8,80	3,00	**2.91**



a/c=0,5 and a/t=0,3			
N(cycle)	**2c(mm)**	**experimental**	**Fuzzy Logic**
180000	3,10	1,10	**1.18**
185000	3,40	1,18	**1.28**
190000	3,80	1,30	**1.30**
195000	4,20	1,40	**1.48**
200000	4,50	1,50	**1.79**
208000	5,40	1,80	**1.94**
214000	6,30	2,10	**2.33**
215000	6,70	2,25	**2.50**
216000	7,10	2,40	**2.65**
217000	7,40	2,50	**2.71**
218000	8,00	2,70	**2.74**
219000	8,60	2,90	**2.85**
220000	9,30	3,10	**3.02**

a/c=0,5 and a/t=0,4			
N(cycle)	**2c(mm)**	**experimental a(mm)**	**Fuzzy Logic prediction a(mm)**
150000	5,15	1,38	**1.44**
155000	5,55	1,55	**1.54**
161000	6,40	1,85	**1.68**
164000	7,00	2,00	**1.89**
169000	7,60	2,15	**2.07**
172000	8,10	2,25	**2.15**
174000	8,70	2,40	**2.19**
175000	9,50	2,60	**2.40**
177000	9,90	2,70	**2.59**
178000	10,50	2,80	**2.69**
179000	12,00	2,90	**2.79**
180000	13,00	3,00	**2.94**

a/c=0,5 and a/t=0,5			
N(cycle)	**2c(mm)**	**experimental a(mm)**	**Fuzzy Logic prediction a(mm)**
158000	6,30	1,65	**1.71**
162000	6,80	1,80	**1.82**
166000	7,20	2,00	**2.14**
168000	7,60	2,20	**2.33**
170000	8,05	2,40	**2.35**
172000	8,30	2,60	**2.58**
174000	9,30	3,00	**2.91**

The measured and predicted *a-N* curves, for *a/c*=0.2; *a/t*=0.2~0.5 initial values are shown in (Fig. 4).

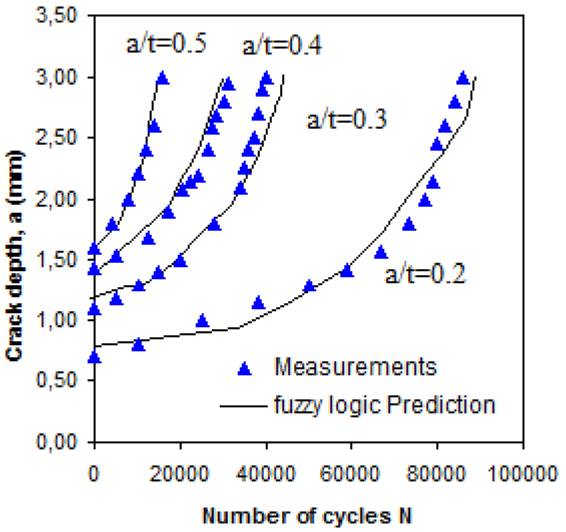


Fig.5 Variations the measured and the predicted crack depths with the number of cycles for a/c=0.5

VI. Conclusions

Fatigue growth rates of surface cracks in axial loading have been conducted. Axial fatigue tests were carried out for 12 Hz frequency, stress ratio *R*=0,1 and for various crack parameters in the ranges of a_0/c_0=0.5, a_0/t= 0.2~0.5. Some remarks are concluded for the crack growth behavior and given below:

1- Fuzzy Logic Method approach can be used for crack growth prediction of elliptical surface cracks in 5086 Al-Mg alloy.

2- Crack growth rates decrease with increasing a_0/t ratios for a constant a_0/c_0 ratio. Growth rate in length direction are considerably higher than in depth direction for all crack forms in this study.

3- Fuzzy logic methods and experimental values were about the same. Maximum deviation between the values of 5-8% was observed.

4- If the elliptical surface cracks growth is mesaured. The depth direction growth would be predicted

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