IJERST

International Journal of Engineering Research and Science & Technology

ISSN : 2319-5991
Vol. 4, No. 3
August 2015

www.ijerst.com

Email: editorijerst@gmail.com or editor@ijerst.com

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Vol. 4, No. 3, August 2015

Research Paper

EFFECT OF STRAIN HARDENING ON FATIGUE CRACK CLOSURE IN ALUMINUM ALLOY

Nirpesh Vikram[1]* and Raghuvir Kumar[1]

Corresponding Author: **Nirpesh Vikram ✉ nirpesh.vikram@gmail.com*

In this study effect of strain hardening on crack closure has been examined with the help of finite element method on the side edge notched specimen of five different Aluminum alloy (3003 Al, 5052 Al, 6061 T6, 6063 T6, 6351) in mode I under constant amplitude fatigue loadingusing Abaqus® 6.10 which is very well accepted FEM applicationin research. Extended Finite Element Method Module has been used to determine plastic strains and stresses at the crack tip while propagation takes place. Experiments have also been done at R-0.1, 0.2, 0.3, 0.5 on constant amplitude fatigue loading. Analytical results have given good agreement with experimental results. Regression analysis has also been done with SPSS® 16 to check the dependency of strain hardening coefficient on crack closure. A generalized empirical formula has been developed based on strain hardening to calculate stress intensity range ratio and a modified Paris law has also been formulated for these aluminum alloy.

Keywords: Fracture Mechanics, Strain Hardening, Abaqus®, Fatigue, Crack Closure, SPSS®

INTRODUCTION

Failures of components and structures over years have encouraged the researchers to perform the various failure studies. In general failure of the components is results of two most common reasons one is fatigue loading and other one is effect of working environment in which the component is working like temperature, the most common factor for environment affected failure (Pearson, 1975). In real life there are mostly complex loading conditions in which the components work but at the time of analysis whether it can be experimental, analytical or numerical we consider the ideal loading condition to get the solutions easily or to form some empirical formulas. Fatigue is the most common cause of crack initiation and crack growth to critical size [16, 69], at which sudden fracture takes place.

It was realized that crack extension takes place due to stress concentration at the crack tip and due to failure of material during cyclic loading; an effort has been made to relate the crack growth with stress intensity factor "K" at the crack tip. A well-established relationship was given by Paris and Erdogan (1963) and takes the following form:

[1] BBDNIIT, Lucknow, India.

$$\frac{da}{dn} = C(\Delta K)^m \quad ...(1)$$

where “C” and “m” depend on material specimen geometry and loading. It is found that for different values of stress ratios, R, for the same material a large deviation in data was obtained from the curve fitted by Equation (1). The use of the range of cyclic stress intensity factors to describe fatigue crack growth rate is based on the assumption that the crack tip starts to open as soon as load is completely relaxed. In 1968 on the basis of results of experiments, Elber (Rice, 1969; Nipesh *et al.,* 2013; 2014) predicted that cyclic plasticity gives rise to the development of residual plastic deformation in the vicinity of the crack tip causing the fatigue crack to close under a positive load. He described this as crack closure phenomenon and suggested that the fatigue crack growth can occur only during the portion of the loading cycle in which the crack is fully open. Based on this suggestion, an effective stress range is defined:

$$\Delta\sigma_{eff} = \sigma_m - \sigma_o \text{ (or } \sigma_{cl}\text{)} \quad ...(2)$$

The ratio of $\Delta\sigma_{eff}$ to the total stress range ($\Delta\sigma$) is defined as the stress intensity range ratio, U, and is given by

$$U = \frac{\Delta\sigma_{eff}}{\Delta\sigma} = \frac{\sigma_m - \sigma_0(or\sigma_{cl})}{\sigma_m - \sigma_n} \quad ...(3)$$

Elber (1968) further suggested that the crack growth relationship be written in the following form:

$$\frac{da}{dN} = C(\Delta K_{eff})m = C(U\Delta K)^m \quad ...(4)$$

The crack propagation equation is written in terms of ΔK_{eff}, instead of $\Delta\sigma$. the factors which have been reported to influence U are stress intensity range ($\Delta\sigma$), material properties (σ_y, σ_f), crack length (a) and stress ratio R. In the work of Elber (1968), however, U is shown to depend only on stress ratio R. Many laws are available which give crack growth rate as a function of ΔK and material properties. In this regards many other researchers (Braithwaite, 1854; Ewing, 1903; Orowon, 1939; Wells, 1963; Walker, 1970; Barsom, 1974; Pearson, 1975) had given their contribution to formulate the crack growth. In the present study, effort has been made to show the effect of strain hardening on crack closure for 3003, 5052, 6061, 6063, 6351 Aluminum alloy. Side Edge Notch (SEN) Specimen is considered in this study.

MATERIALS AND SPECIMEN GEOMETRY ANALYZED

Material Properties

Five Aluminum Alloy have been used to prepare

Table 1: Chemical Composition

	Element								
Material									
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other
6061 T6 Al	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.4
6063 T6 Al	0.30-0.70	0.6	0.1	0.3	0.40-0.90				0.4
6351 Al	0.7-1.3	0.5	0.1	0.4-0.8	0.4-0.8		0.2	0.2	
3003 Al	0.6	0.7	0.05-0.20	1.0-1.5			0.1		
5052 Al	0.25	0.4	0.1	0.1	2.2-2.8	0.15-.35	0.1		-

Table 2: Physical Properties

	Element					
Material	s_y	s_u	s_f	Ex10^6	Elongation%	Reduction in Area %
6061 T6 Al	30.14	32.5	45	7	10.5	28.3
6063 T6 Al	21	24.2	64	7	10.6	60
6351 Al	174.7	179.31	129.3	14.76	17	50
3003 Al	153	157	8	16	8	18.7
5052 Al	195	230	105		32	

specimens are 3003 Al, 5052 Al, 6061-T6 Al, 6063-T6 Al, 6351 Al that's chemical and mechanical properties are given in Tables 1 and 2, respectively.

SPECIMEN GEOMETRY

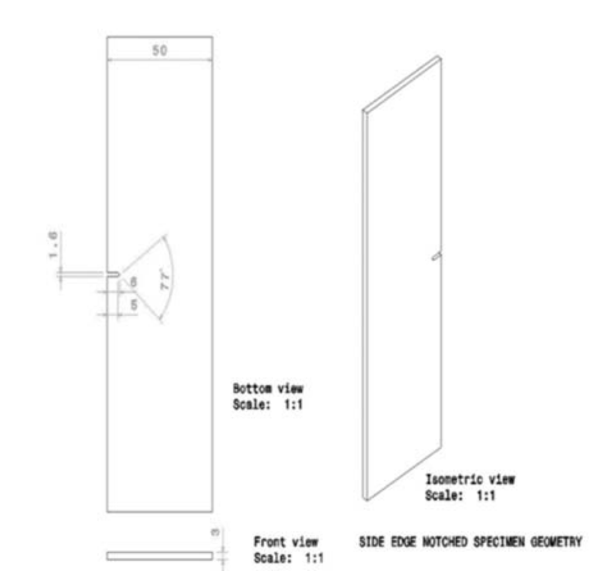
Specimen has been modeled with the dimensions of

Length (H)- 180 mm

Width (W) - 50 mm

Thickness (t) – 3 mm

Figure 1: Specimen Geometry



Initially a notch of 6 mm had been made at en edge for crack propagation under the load applications on the specimen during the fatigue test. The geometry is shown in Figure 1.

METHODOLOGY

The methodology adopted for this study has certain specific steps which start from experiments for fatigue testing of the specimen given in Figure 1 on MTS machine and result data collected for the validation with finite element method and tabulated all result parameters together to perform regression analysis to determine the dependency of strain hardening on fatigue crack closure. All steps are shown in Figure 2.

Figure 2: Flow Diagram of Methodology

FINITE ELEMENT ANALYSIS OF CRACK

3D Modeling Using Catia V5 R19

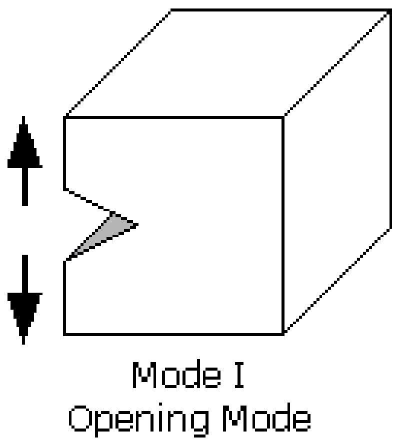
3D modeling of specimen had been done on CATIA V5 R19 as shown in Figure 1 the dimensions of the specimen were based ASTM standard for fatigue testing and then it has been imported to Abaqus 10 as a deformable solid part.

Fem Modeling

A crack had been developed in Abaqus 10 itself as a shell deformable part. After modeling both the instances were called in assemble module to insert the crack in the specimen. C3D8R elements were used to mesh the specimen but not the crack. Crack remains unmeshed throughout the analysis. Because the whole analysis were done for Mode I as Figure 2 so that one side of the specimen were kept fixed and other end was loaded.

XFEM module were used to study the onset and propagation of cracking in quasi-static problems. XFEM allows us to study crack growth along an arbitrary, solution-dependent path without needing to remesh our model. We can choose to study a crack that grows arbitrarily through our model or a stationary crack. We defined an XFEM crack in the Interaction module. We specified the initial location of the crack. Alternatively, we allowed Abaqus to determine the location of the crack during the analysis based on the value of the maximum principal stress or strain calculated in the crack domain.

Figure 3: Mode I Fracture Modes



Initial Conditions

Initial values of stresses, temperatures, field variables, solution-dependent state variables, etc., specified as follows.

Boundary Conditions

Specimen has been kept in mode I fracture mode that is called as crack opening mode as shown in Figure 3 in this mode tensile forces are exerted on the top and bottom face of the specimen in this case displacement will be normal to the crack surface.

Boundary conditions applied to the displacement or rotation degrees of freedom for the SEN Specimen. One side kept fixed (use Encastre Boundary condition) and on other side stress applied. During the analysis, boundary conditions had an amplitude definition that is cyclic over the step.

Loads

Following loading conditions were considered:

Case 1: Pmax = P min = 0, P max = 14 kN, R = 0

Case 2: Pmin = 1.4kN, P max = 14 kN, R = 0.1

Case 3: P min = 4.2kN, P max = 14 kN, R = 0.3

Case 4: P min = 7kN, P max = 14 kN, R = 0.5

Figure 4: Abaqus screenshot of Simulation

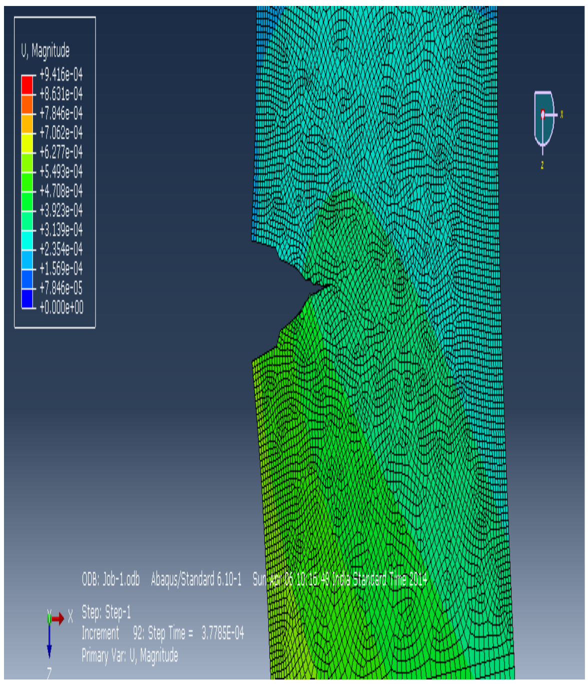
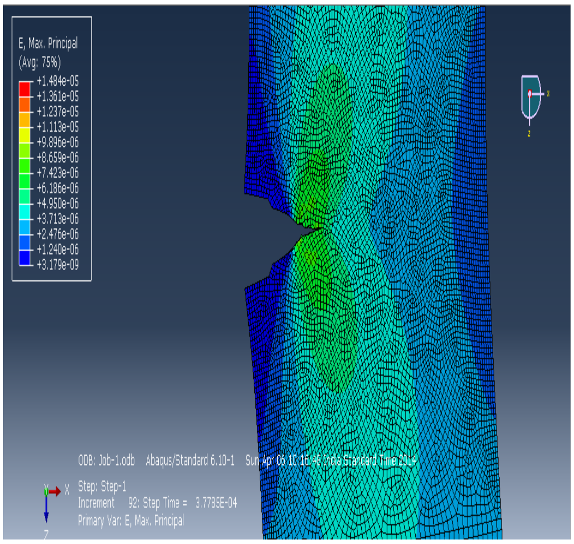


Figure 4 (Cont.)



Fields Output

Fields output variables 'PHILSM', 'PSILSM' and STATUSXFEM under the Failure/Fracture and Status category respectively are selected to calculate crack length with no of load cycle.

Result Visualization

REGRESSION ANALYSIS

After FEM analysis, Linear Regression analysis was done on SPSS 10. From the output we have drawn the graphs between UVs n fitted the trend line and got coefficients value for trend line equation for each material. After getting equation for each material we formed a generalized equation that suits the result of all other materials

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	**Std. Error**	**Beta**	**T**	**Sig.**
N	0.818	.000	.179	-.871	.000
(Constant)	.704	.000		221601	.000

6063-T6 Al Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	**Std. Error**	**Beta**	**T**	**Sig.**
n	.960	.001	.096	.612	.000
(Constant)	.176	.002		380.804	.000

6061-T6 Al Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	**Std. Error**	**Beta**	**T**	**Sig.**
N	803	.000	-.068	-.430	.669
(Constant)	.695	.000		1957.460	.000

6351 Al Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	**Std. Error**	**Beta**	**T**	**Sig.**
N	.621	.000	.121	.770	.000
(Constant)	1.35	.001		1319.334	.000

5052 Al Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	**Std. Error**	**Beta**	**T**	**Sig.**
N	.907	.015	.100	.481	.635
(Constant)	.450	.048		10.753	.000

Material	**Equations after Regression Analysis**
3003 Al	U= 0.803*n + 0.695
5052 Al	U=0.907*n + 0.450
6061 T6 Al	U = 0.818*n + 0.704
6063 T6 Al	U = 0.96*n + 0.176
6351 Al	U = 0.621*n+1.35

and with the help of this we can predict the approximation for crack closure of other Aluminum alloys too.

The scheme of the curves is given below.

Validation of the Generalized Equation:

Material	U (by generalized Equation) For n=3.3	U (by individual equation) For n=3.3	Variation (%)
3003 Al	3.3944	3.3449	1.47986
5052 Al	3.3944	3.4431	1.559641
6061 T6 Al	3.3944	3.4034	0.411353
6063 T6 Al	3.3944	3.3704	0.56373
6351 Al	3.3944	3.3993	0.291236

GENERALIZED RESULT

With the help of these equations we can form a generalized equation

i.e. $U = 0.818*n+0.695$

MODIFIED PARIS LAW

Putting the above relationship between U and n we can easily modify Paris Relationship which is very well suitable for aluminum alloy

$$da/dN = C\{(0.818 * n + 0.695)\Delta K\}^n$$

CONCLUSION

A plane stress analysis using XFEM and thereafter regression analysis at different stress range ratio were performed on side edge notched specimen and effect of strain hardening on crack closure were noticed that the value of effective stress intensity range ratio (U) increases with the increasing strain hardening exponent at the crack tip. A generalized relationship was formed for evaluation of U accordingly a modified Paris relationship was obtained.

REFERENCES

1. Barsom J M and McNicol R C (1974), "Effect of stress concentration on fatigue crack initiation in HY-130 Steel, ASTM STP 559", American Society for Testing and Materials, Philadelphia, pp. 183-204.

2. Basquin O H (1919), "The Exponential Law of Endurance Tests", *Proc. Annual Meeting ASTM*, Vol. 10, pp. 625.

3. Braithwaite F (1854), "On the Fatigue and Consequent Fracture of Metals", *Minutes of Proc. ICE*, p. 463.

4. Burdekin F M and Stone D EW (1966), "The Crack Opening Displacement Approach to Fracture Mechanics in Yielding Materials", *Journal of Stress Analysis,* Vol. 1, p. 145.

5. Chand S and Garg S B L (1985), "Crack Propagation Under constant Amplitude Loading", *Engineering Fracture Mechanics*, Vol. 21, No. 1, pp. 1-30.

6. Chang T and Guo W (1999), "Effects of strain hardening and stress state on fatigue crack closure", *International Journal of Fatigue,* Vol. 21, pp. 881-888.

7. Coffin Manson (1955), "Introduction to high-temperature low-cycle fatigue", *Experimental Mechanics*, Vol. 8, No. 5, pp. 218-224.

8. Elber W (1968), "Fatigue Crack Propagation: Some Effects of Crack Closure on the Mechanism of Fatigue Crack Propagation under Cyclic Tension Loading", Ph.D. Thesis, University of New South Wales.

9. Ewing J A and Humfrey J C W (1903), "The Fracture of Metals under Repeated Alternations

of Stress", *Philosophical Transactions,* Royal Society London, CC, p. 241.

10. Griffith A A (1920), "The Phenomena of Rupture and Flow in Solids", *Philosophical Transactions A,* Vol. 221, p. 163.
11. Inglis C E (1913), "Stresses in a Plate due to the Presence of Cracks and Sharp Corner.", *Transactions of the Institute of Naval Architects*, Vol. 55, p. 219.
12. Irwin G R (1958), *Fracture, Handbuch der physic*, S. Flugge(ed.), Springer-Verlag, Berlin, Vol. VI, pp. 551-590.
13. Rice J R (1969), "A path Independent Integral and Approximate Analysis of Strain Concentration by Notches and Cracks", *Journal of Applied Mechanics*, Vol. 35, pp. 379-386.
14. Hertzberg Richard W (1989), *Deformation and Fracture Mechanics of Engineering Materials*, John Wiley & Sons, New York.
15. Lin X B and Smith R A (1999), "Finite element modeling of fatigue crack growth of surface cracked plates", Part I: The numerical technique. Engineering Fracture Mechanics, Vol. 63, pp. 503-522.
16. Neuber H (1961), "Theory of Stress Concentration for Shear-Strained Prismatical Bodies with Arbitrary Nonlinear Stress Strain Law", *Journal of Applied Mechanics,* Vol. 28, p. 544.
17. Nicolas Mooesy, John Dolbowz and Ted Belytschko (1999), "A finite element method for crack Growth without remeshing", *International Journal For Numerical Methods In Engineering, Int. J. Numer. Meth. Engng.,* Vol. 46, pp. 131-150.
18. Niccolls E H (1976), "A Co-relation for Fatigue Crack Growth Rate", *Scripta Metall,* Vol. 10, pp. 295-298.
19. NirpeshVikram and Raghuvir Kumar (2013), "Review on Fatigue-Crack Growth and Finite Element Method", *International Journal Of Scientific & Engineering Research,* Vol. 4, Issue 4, Issn 2229-5518, pp. 833-843.
20. Nirpesh Vikrm, Sakshi Agrawal andRaghuvir Kumar (2014), "Effect of Strain Hardening on Crack Growth Rate", *SYLWAN*, Vol. 158, No. 6, pp. 110-124.
21. Orowan E (1939), "Theory of the Fatigue of Metals", *Proc. Royal Society A*, Vol. 171, p. 79.
22. Orowan E (1948), "Fracture and Strength of Solids", *Reports on Progress in Physics*, Vol. 12, p. 185.
23. Osgood C C (1982), "Fatigue Design", Cranburry, New Jersey, USA, Peragamon Press.
24. Paris P C and Erdogan F (1963), "A Critical Analysis of Crack Propagation Laws", *Journal of Basic Engineering*, Vol. 85, p. 528.
25. Peterson R E (1953), "Stress Concentration Design Factors", John Wiley, New York.
26. Pearson S (1975), "Initiation of Fatigue Cracks in Commercial Aluminum Alloys and the Subsequent Propagation of Very Short Cracks", *Engineering Fracture Mechanics*, Vol. 7, p. 235.
27. Shiozawa K and Matsushita H (1998), "Crack Initiation and Small Fatigue Crack Growth Behavior of Beta Ti-15V-3Cr- 3Al-3Sn Alloy", Proc. Fatigue '96, G. Lutjering H Nowack (Eds.), Berlin (1996) 301Couroneau N, Royer J, Simplified model for the fatigue

crack growth analysis of surface cracks in round bars under mode I, *International Journal of Fatigue,* p. 711.

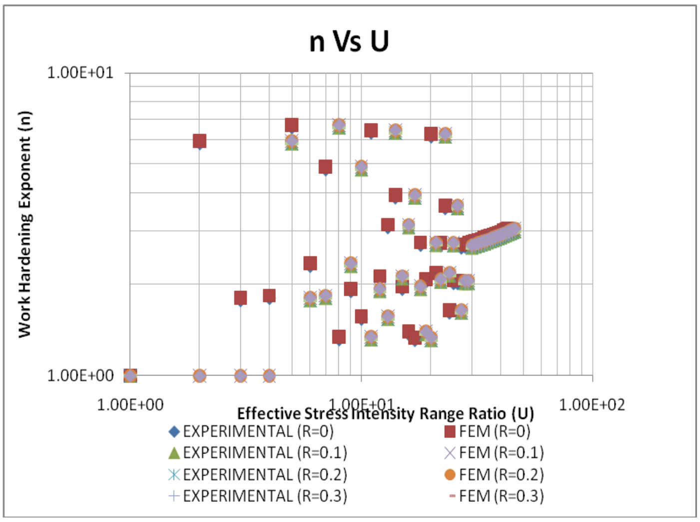
28. Sukumarz N, Mooesx N, Moran B and Belytschko T (2000), "Extended finite element method for three-dimensional crack modeling", *International Journal of Fatigue,* Vol. 21, pp. 801-823.

29. Wells A A (1963), "Application of Fracture Mechanics at and beyond general yielding", *British Welding Journal*, Vol. 10, pp. 563-570.

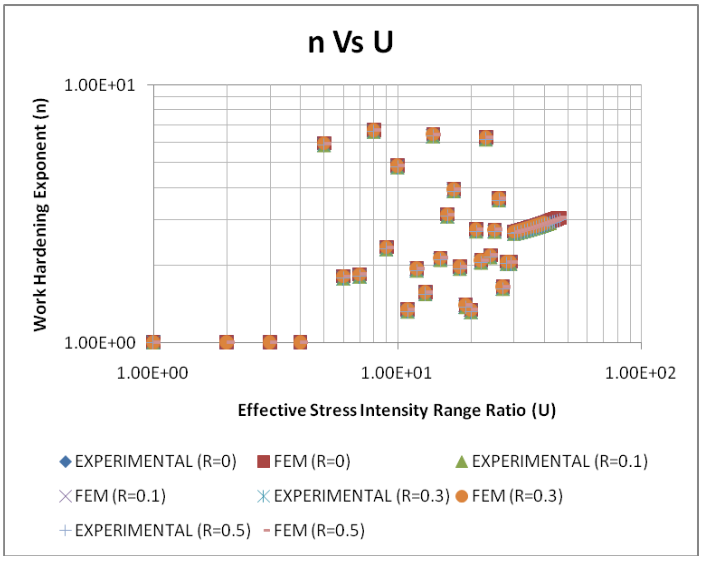
30. Walker K (1970), "The Effect of Stress Ratio During Crack Propagation & Fatigue for 2024-T3 and 7075-T6 aluminum", *ASTM STP,* Vol. 462, pp. 1-14.

APPENDIX

Result Visulalization



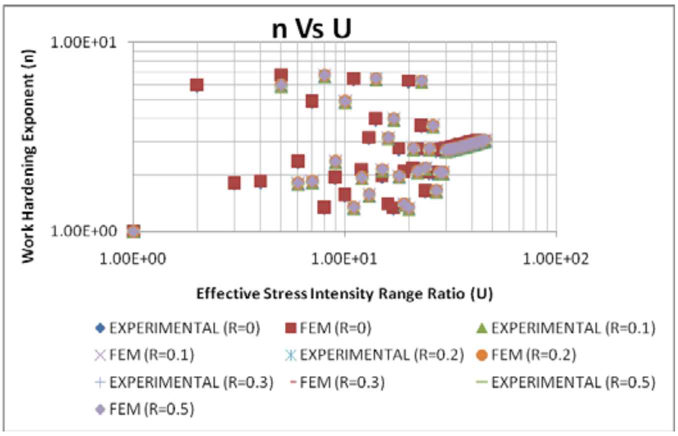
ÄP = Constant, 3003 Al



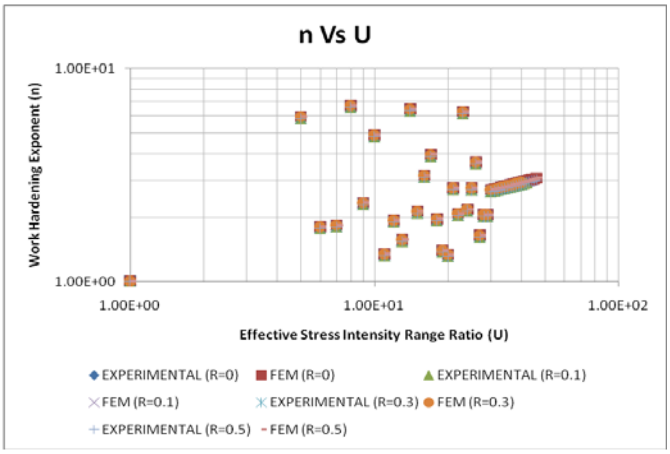
P_{max}=Constant, 300Al

APPENDIX (CONT.)

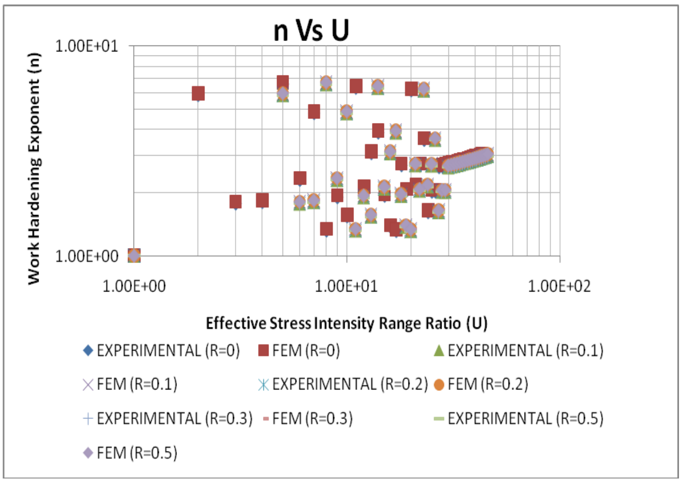
Result Visulalization



5052 Al, ÄP= Constant



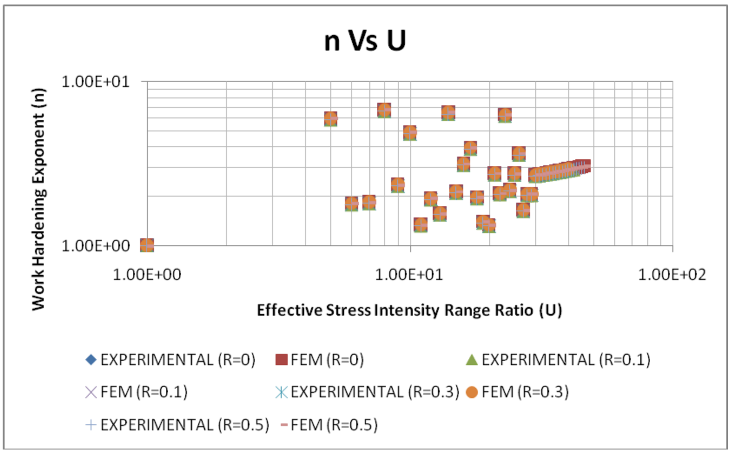
5052 Al, P_{max}= Constant



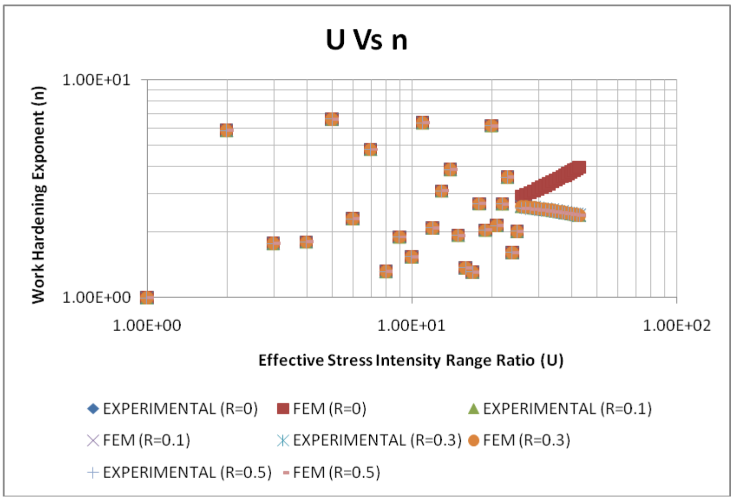
6061-T6 Al, ÄP= Constant

APPENDIX (CONT.)

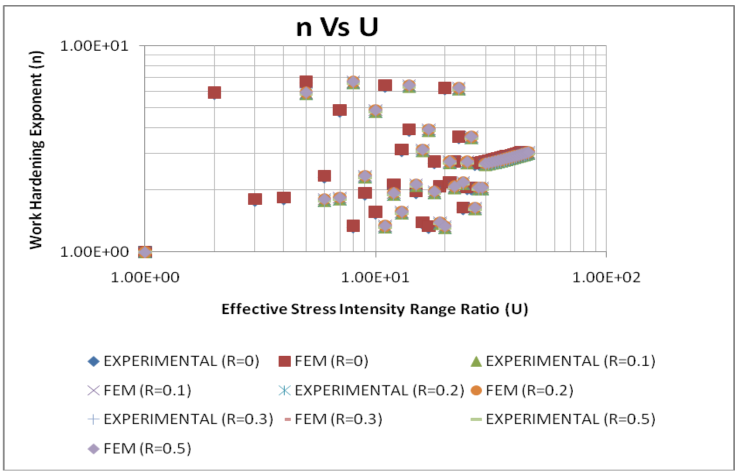
Result Visulalization



6061-T6 Al, P_{max}=Constant



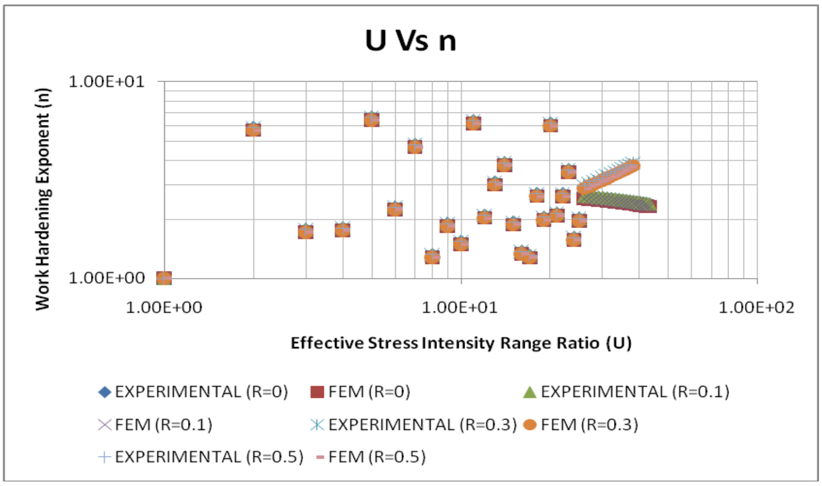
6063-T6 Al, P_{max}= Constant



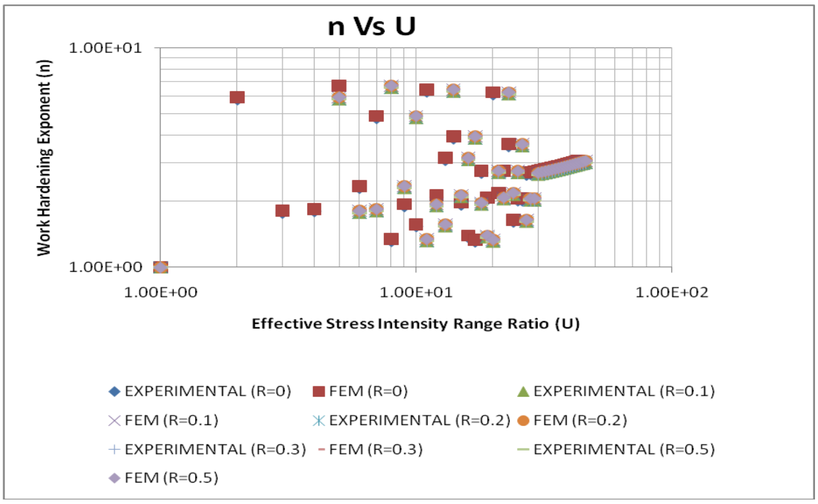
6063-T6 Al, ÄP=Constant

APPENDIX (CONT.)

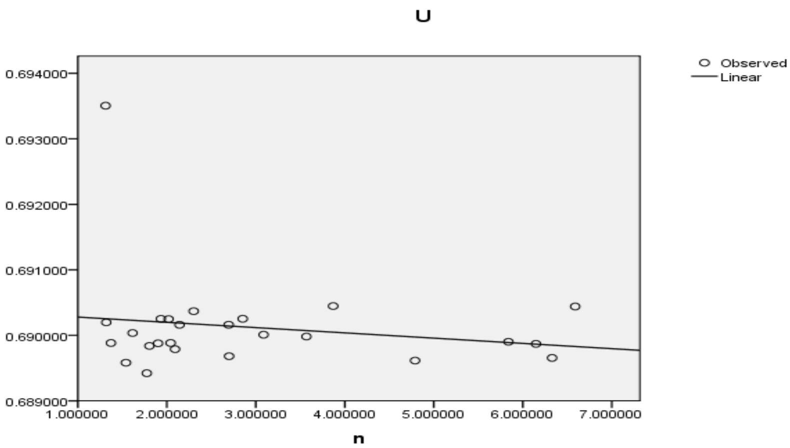
Result Visulalization



6351-T6 Al, ÄP=Constant



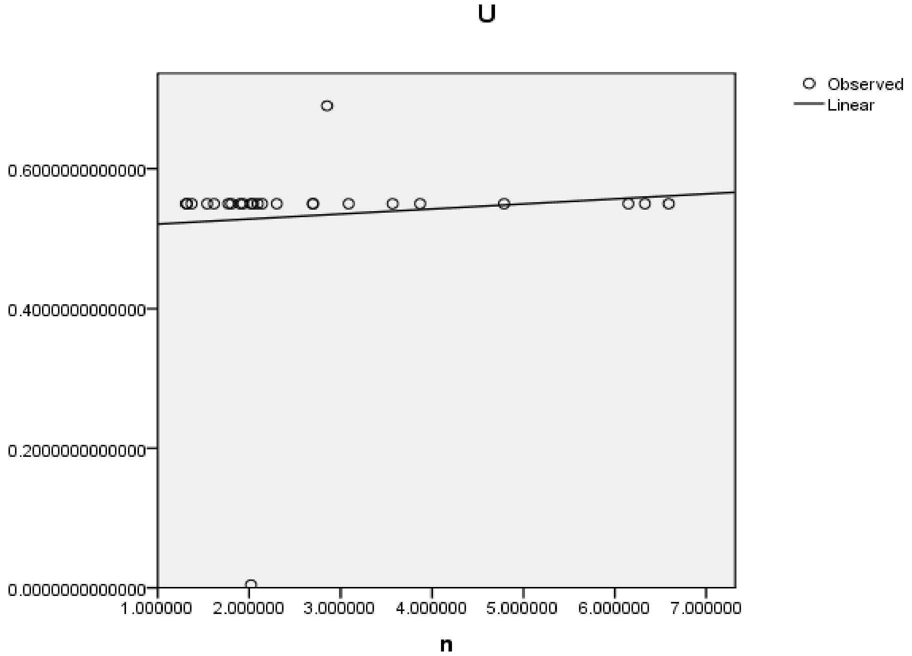
6351 Al P_{max}=Constant



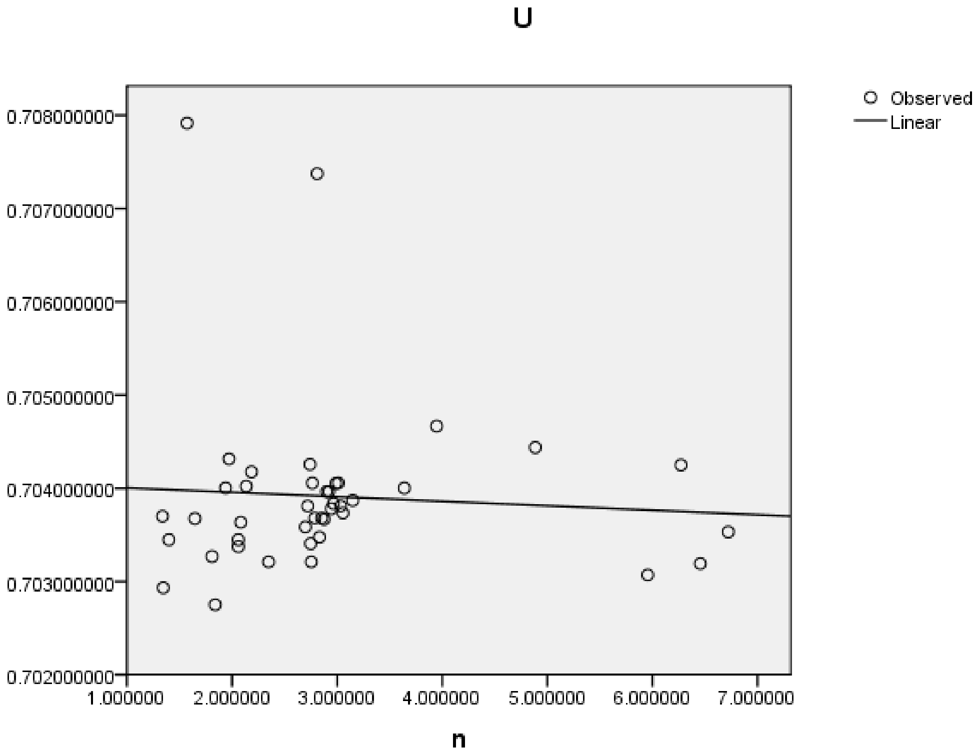
3003 Al

APPENDIX (CONT.)

Result Visulalization



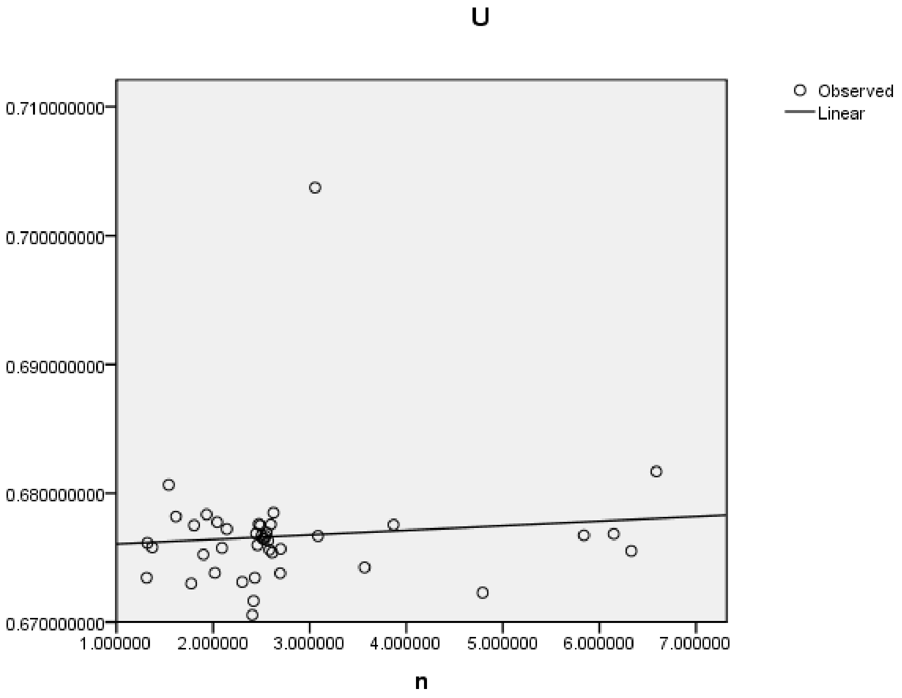
5052 Al



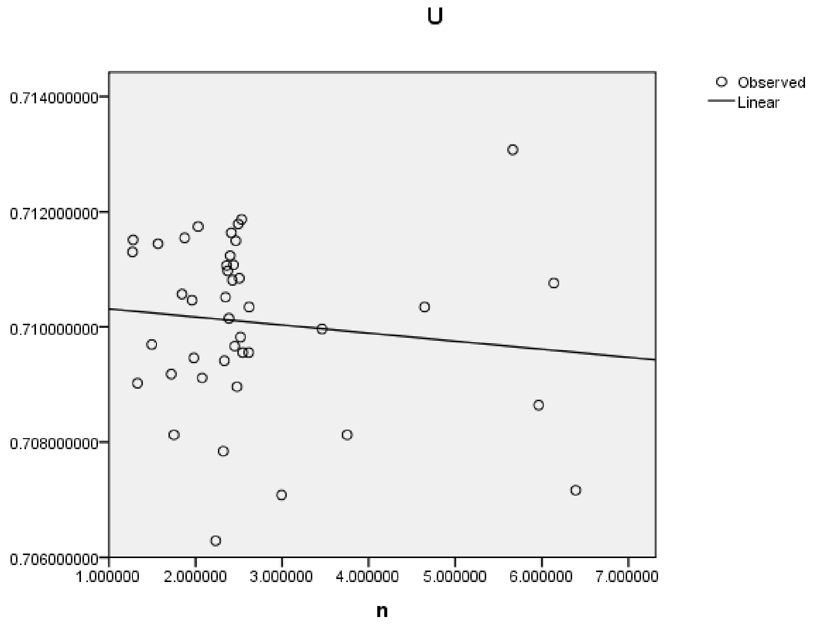
6061-T6 Al

APPENDIX (CONT.)

Result Visulalization



6063-T6 Al



6351 Al

NOMENCLATURE

Greek Symbols	Description
á	A variable factor
ó	Normal stress
$ó_a$	Average (mean) stress in a cycle
$ó_m$	Maximum stress in a cycle
$ó_n$	Minimum stress in a cycle
$ó_o$	Optimum stress
$ó_p$	Stress amplitude in a cycle
$ó_u$	Ultimate stress
$ó_y$	Yield stress
$\Delta ó$	Stress range

English Symbols	Description
a	Crack length
C	Constant of crack growth equation
$\frac{da}{dN}$	Crack growth rate
E	Young's modulus of elasticity
K	Stress intensity factor
ΔK	Stress intensity range
m	Exponent of crack growth rate equation
n	Exponent of crack growth rate equation
N	Number of cycles

NOMENCLATURE (CONT.)

N_f	Number of cycles to failure
P	Simple load
P_m	Maximum load in a cycle
P_n	Minimum load in a cycle
ΔP	Load range in a CAL cycle
R	Stress ratio in CAL cycle
W	Width of the specimen

International Journal of Engineering Research and Science & Technology
Hyderabad, INDIA. Ph: +91-09441351700, 09059645577
E-mail: editorijlerst@gmail.com or editor@ijerst.com
Website: www.ijerst.com

ISSN 2319-5991