

Chapter 5

Low Cycle Fatigue Behaviour of Aluminum Alloy AA6063 heat treated at 350°C Temperature for Different Soaking Times

5.1 Introduction

The present chapter deals with Low Cycle Fatigue behavior of as received aluminum alloy AA6063 heat treated at 350°C with different soaking time. A log-log strain-life curve is presented and all fatigue parameters are predicted. The results are verified with that obtained theoretically. The effect of different soaking time on low cycle fatigue properties of aluminium alloy AA6063 have been observed for different soaking time of 2hours, 4hours, 6hours and 8hours at same heat treatment temperature of 350°C. It is observed that the yield stress and ultimate tensile strength continuously decreased with increase in soaking time. The strain hardening exponent n and strength coefficient K increased when the soaking time increased, similarly the fatigue strength exponent b and fatigue ductility exponent c also increased as soaking time increased. Cyclic elastic strain (σ_f'/E) also increases with increase in soaking time at same heat treatment temperature of 350°C.

5.2 Results

Tensile tests were carried out at room temperature and 350°C with various soaking time of 2hours, 4hours, 6hours and 8hours with water solution treatment. Tensile engineering stress-strain curves for different soaking time at constant heat treatment temperature of the alloy AA6063 are shown in Fig. 5.1 to Fig. 5.4.

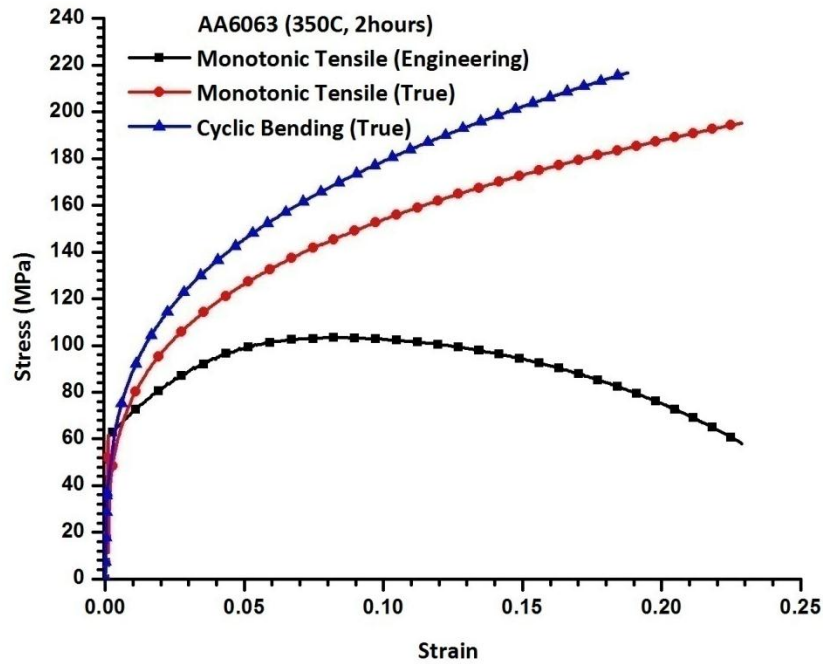


Fig. 5.1 Stress–strain curves for AA6063 alloy at heat treatment temperature of 350°C with 2 hour soaking time

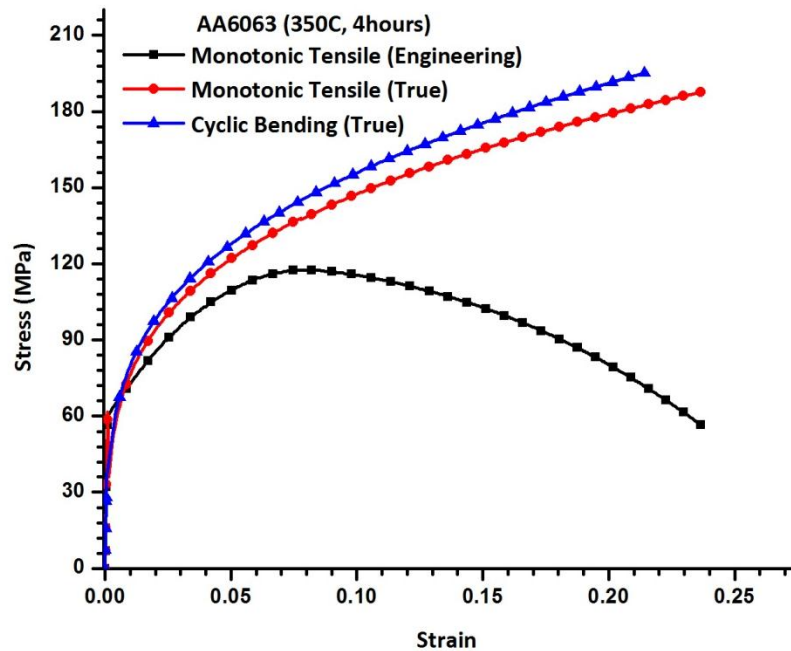


Fig. 5.2 Stress–strain curves for AA6063 alloy at heat treatment temperature of 350°C with 4 hour soaking time

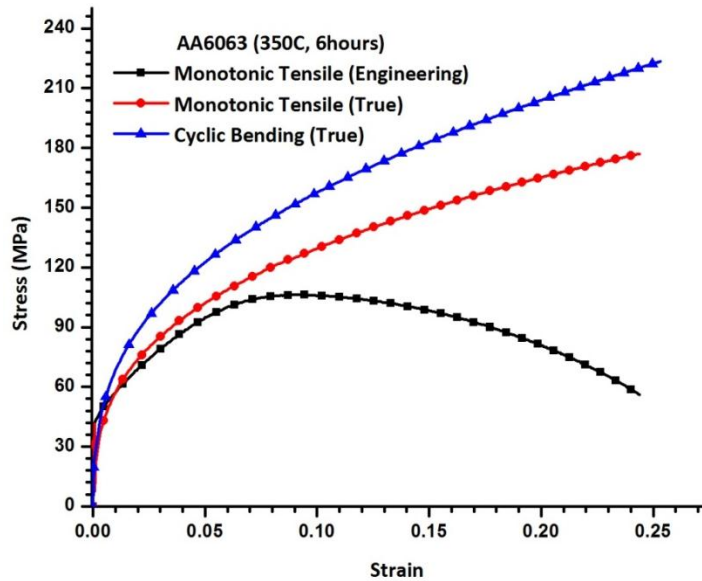


Fig. 5.3 Stress–strain curves for AA6063 alloy at heat treatment temperature of 350°C with 6 hour soaking time

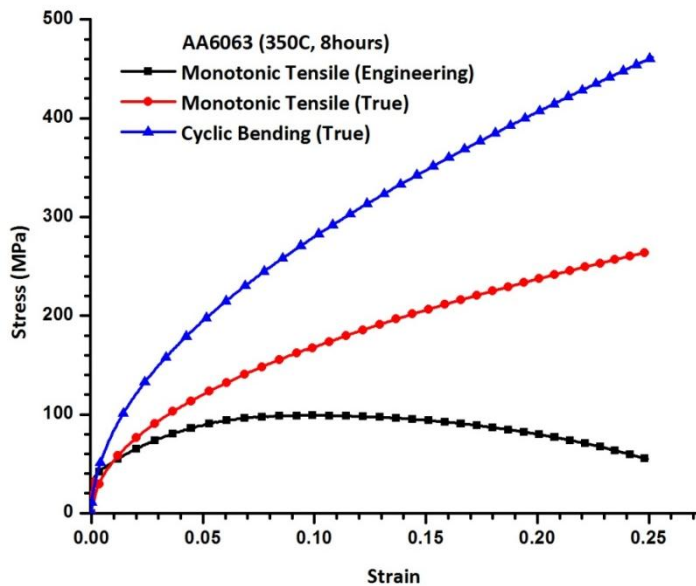


Fig. 5.4 Stress–strain curves for AA6063 alloy at heat treatment temperature of 350°C with 8 hour soaking time

Table 5.1 shows values of n , K , σ_{frac}^{true} , σ_{frac}^{engg} , σ_y , σ_{Max} , ϵ_{frac} , E and for as received AA6063 samples and AA6063 samples at same heat treatment temperature of 350C at different soaking time viz. 2hours, 4hour, 6hours and 8hours.

Table 5.2, 5.3 and 5.4 show comparison of values of n, k and $\sigma_{fracture}^{true}$ obtained experimentally for the heat treatment temperature of 350°C with the different soaking time of 4hours, 6hours and 8hours, respectively, to that obtained by empirical relations given by Eqs. (2.68) to (2.70).

Figure 5.5 illustrates that yield stress and maximum stress decrease with increase in soaking time. However, percent elongation has an increasing tendency with increase in soaking time as shown in Fig. 5.6.

Table 5.1 The monotonic properties of AA6063 at same heat treatment temperature 350°C with different soaking time

Conditions	n	$\sigma_{frac.}^{engg.}$	K	$\sigma_{frac.}^{true}$	σ_y (MPa)	σ_{Max} (MPa)	$\epsilon_{Frac.}$	E (GPa)
As Received	0.25	859.5	776.2	237.49	169.67	214.80	0.2745	68
350°C_2hours	0.28	398.4	338.8	345.91	60.06	117.30	0.2940	60
350°C_4hours	0.27	337.53	288.4	341.15	59.48	106.16	0.3010	58
350°C_6hours	0.342	424.22	343.55	363.5	41.70	106.13	0.2885	57
350°C_8hours	0.49	1196.0	864.9	379.82	34.70	99.10	0.2960	55

Table 5.2 Comparison values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 350°C with 4hours soaking time

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.27	0.30708	0.29287	0.27428
k	286.4	286.4	286.4	327.08
$\sigma_{fracture}^{true}$	341.15	185.14	337.28	187.63

Table 5.3 Comparison values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 350°C with 6hours soaking time

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.342	0.34209	0.34187	0.34569
k	343.55	343.55	343.55	357.4
$\sigma_{fracture}^{true}$	363.5	211.79	539.07	177.08

Table 5.4 Comparison values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 350°C with 8hours soaking time

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.49	0.48969	0.49014	0.48806
k	864.9	864.9	864.9	720.41
$\sigma_{fracture}^{true}$	379.82	437.56	1246.7	264.48

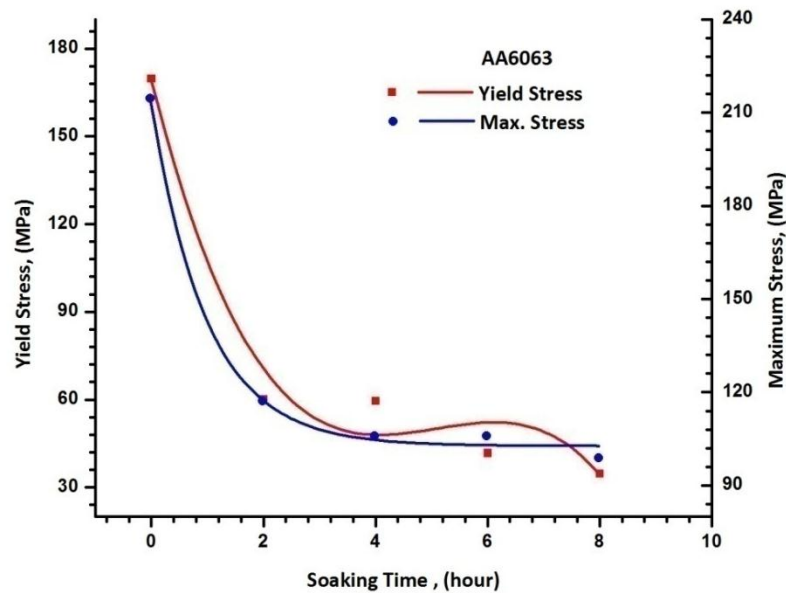


Fig. 5.5 Maximum Stress and Yield Stress variation with different soaking time for AA6063 alloy at same heat treatment temperature of 350°C

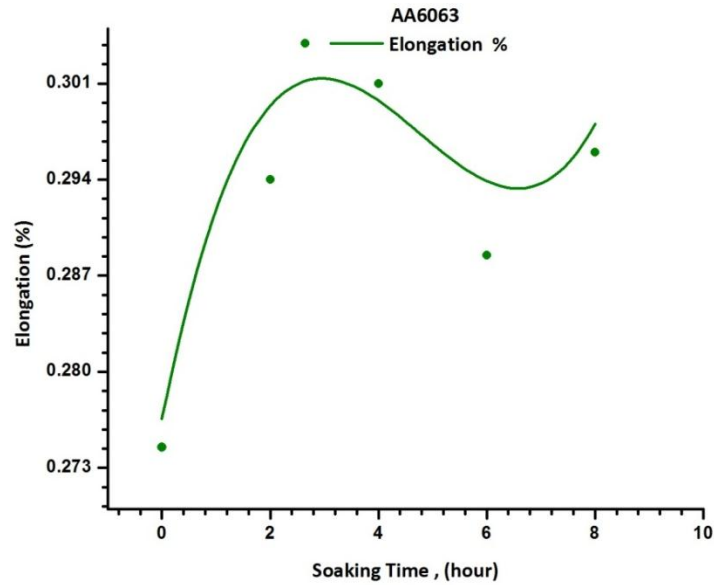


Fig. 5.6 Variation of elongation at same heat treatment temperature of 350°C with different soaking times for AA6063 alloy

True plastic stress versus true plastic strain is plotted in log-log scale for the samples as shown in Fig. 5.7. From this plot strain hardening exponent (n) is determined from the slopes.

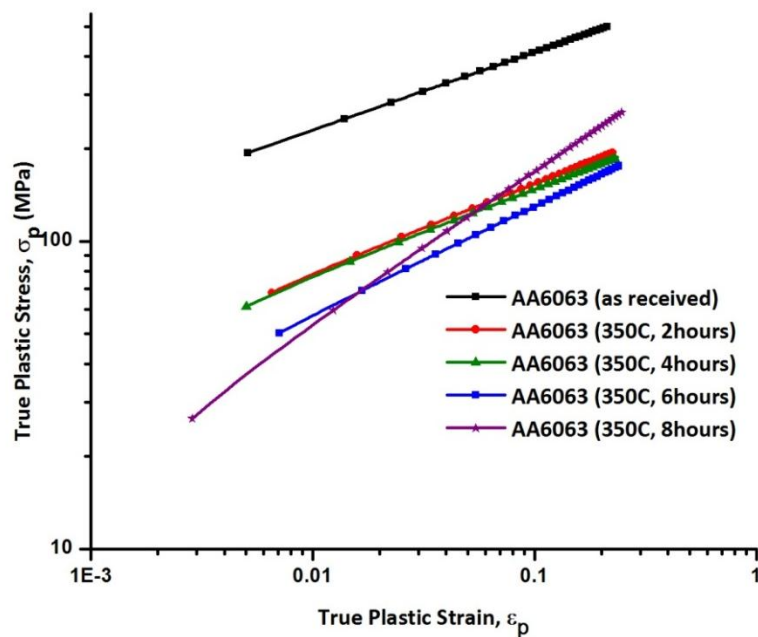


Fig. 5.7 Log-Log true plastic stress versus true plastic strain plot with different soaking time at same heat treatment temperature of 350°C

The strength coefficient (K) is also determined from the intercept on y-axis at $\epsilon_p = 1$, based on the Eq. (2.1) [3,4,9,63]. Figure 5.8 demonstrates the variation of strain hardening exponent (n) and strength coefficient (K) with respect to soaking time.

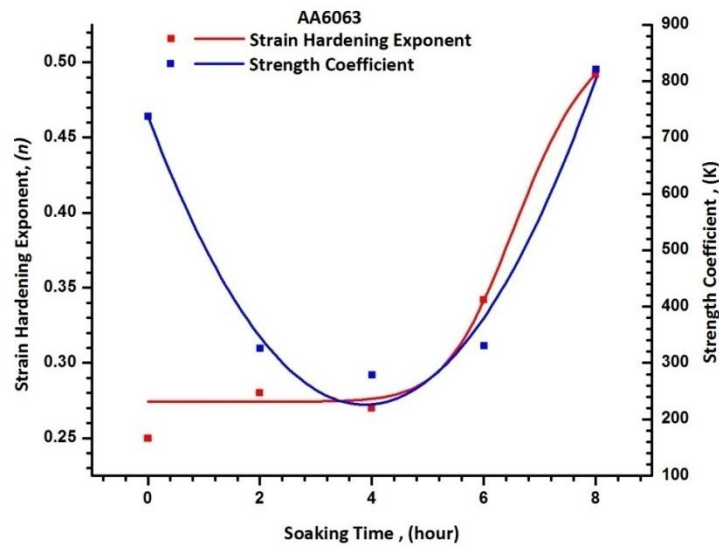


Fig. 5.8 Variation of strength Coefficient (K) and Strain Hardening exponent (n) with different soaking time for AA6063 samples heat treated at same temperature of 350°C

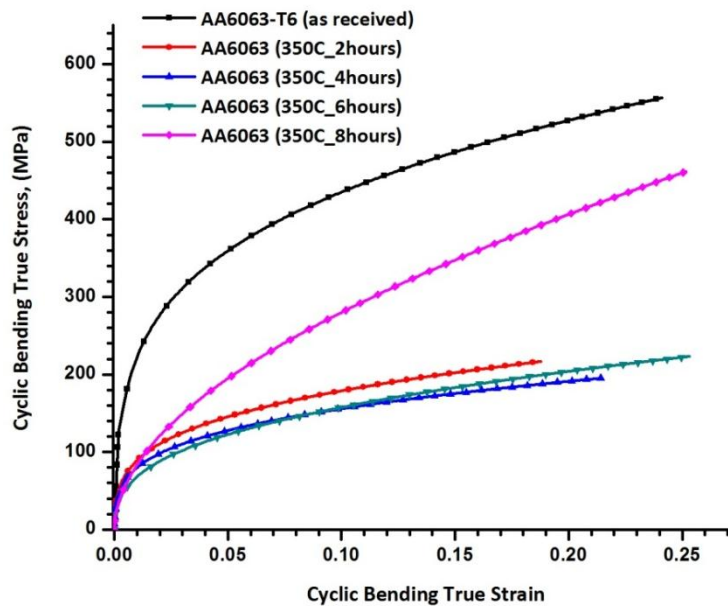


Fig. 5.9 Cyclic Bending True Stress-Strain Curves of AA6063 heat treated at 350°C temperature with various soaking times

Figure 5.9 shows cyclic bending true stress versus cyclic bending true strain curves for as received AA6063 samples heat treated at same temperature of 350°C for different soaking time.

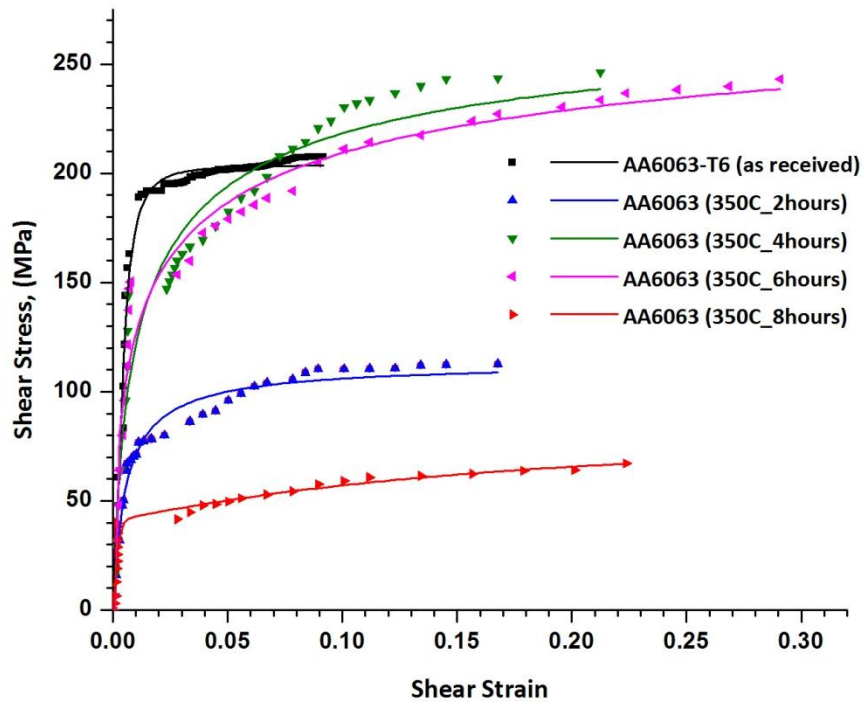


Fig. 5.10 Torsion curves for AA6063 samples for different soaking times with same heat treatment temperature of 350°C

Torsion curves i.e. curve for shear stress versus shear strain for as received AA6063 samples as well as heat treated AA6063 samples for different soaking time at same heat treatment temperature of 350°C is shown in Fig. 5.10 . Different parameters obtained from torsion test are reported in Table 5.5 .

Figure 5.11 illustrates that the maximum shear strain and maximum angle of twist have an increasing tendency with increasing soaking time till 6hours of soaking time , and after that have decreasing tendency upto 8hours of soaking time.

Table 5.5 Torsion test data for AA6063 samples at different soaking times with same heat treatment temperature of 350°C

Parameters	symbol	AA6063-T6 As received	Value of AA6063 at 350°C_2hour	Value of AA6063 at 350°C_4hour	Value of AA6063 at 350°C_6hour	Value of AA6063 at 350°C_8hour
Max. shear strain (Deg)	γ_{\max}	6.4	9.61	12.17	16.66	12.8
Max. angle of twist (Deg)	α_{\max}	100	150	190	260	200
Shear modulus (GPa)	G	25.9	22.3	21.5	21.4	20.6
Toughness (J/m ³)	K_t	914	2276.4	7665	7580	1850.7
Max. shear stress (MPa)	τ_{\max}	209.03	115.112	265.7	254.52	80.2588
Torque (Nm)	T_{max}	641.3	353.16	815.21	780.876	246.231

Shear modulus decreases with increasing soaking time and toughness increases till 6hours of soaking time and then decreases upto 8hours of soaking time as demonstrated in Fig. 5.12.

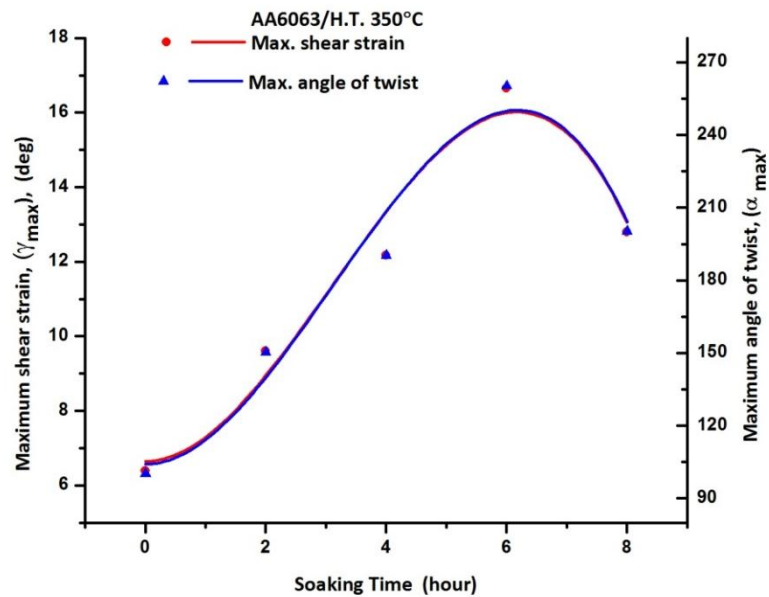


Fig. 5.11 Variation of maximum shear strain and maximum angle of twist with different soaking time at same heat treatment temperature of 350°C

Figure 5.13 shows variation of maximum shear stress and maximum torque with soaking time at heat treatment temperature of 350°C.

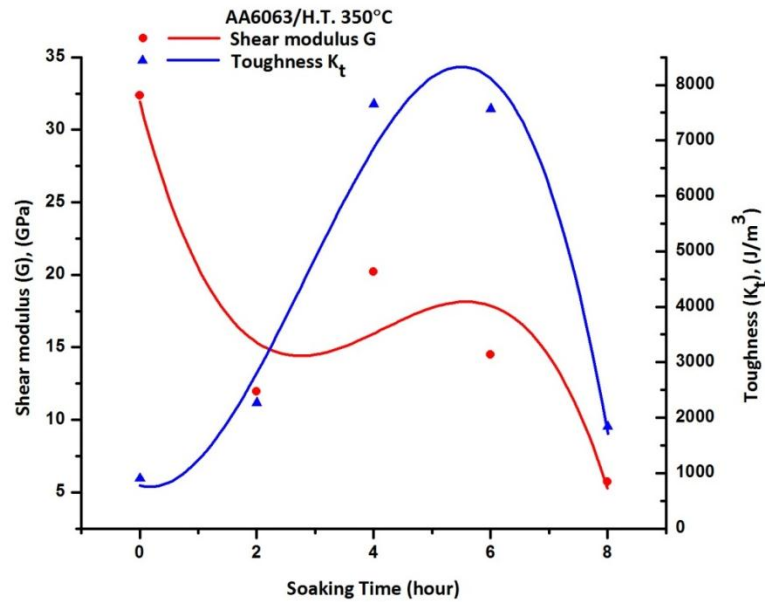


Fig. 5.12 Variation of shear modulus and toughness with different soaking time at same heat treatment temperature of 350°C

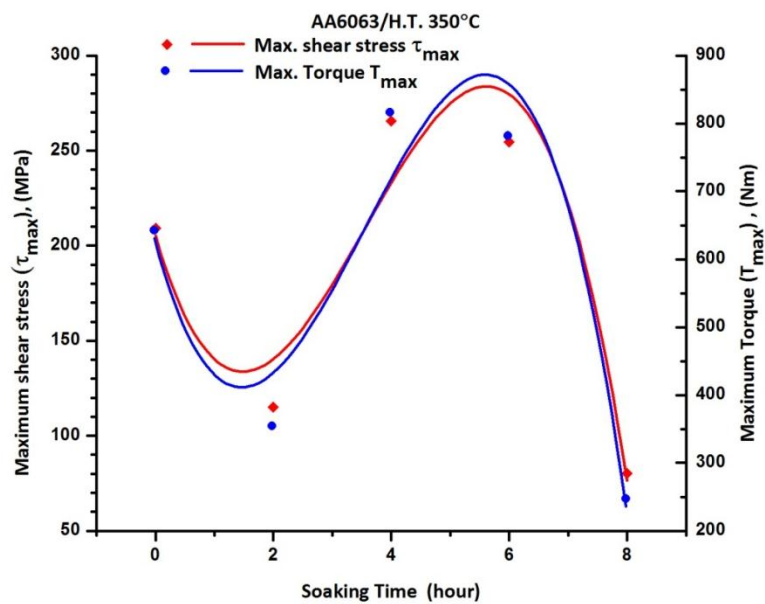


Fig. 5.13 Variation of maximum shear stress and maximum torque with different soaking time at same heat treatment temperature of 350°C

Cyclic data have been collected from the rotating cantilever fatigue test for AA6063 sample having heat treated at 350°C for soaking time of 2 hours and provided in Table 5.6. The strain life relation is plotted for this sample and shown in Fig. 5.14. The plot illustrates elastic strain line, plastic strain line and total strain curve. The plot also shows transition fatigue life (N_T) and two regions viz. elastic region and plastic region.

Table 5.6 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 350°C and with soaking time of 2 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
1160785	0.00123	0.00431	0.00554
60534	0.00142	0.00716	0.00858
53210	0.00158	0.01055	0.01213
37963	0.00176	0.01557	0.01733
13890	0.00193	0.0216	0.02353
10090	0.00211	0.02943	0.03154
9899	0.00222	0.03504	0.03726
6991	0.00229	0.03912	0.04141
5703	0.00235	0.04324	0.04559
5266	0.00246	0.05028	0.05274
2464	0.00264	0.06402	0.06666
860	0.00281	0.08011	0.08292
613	0.00299	0.09838	0.10137

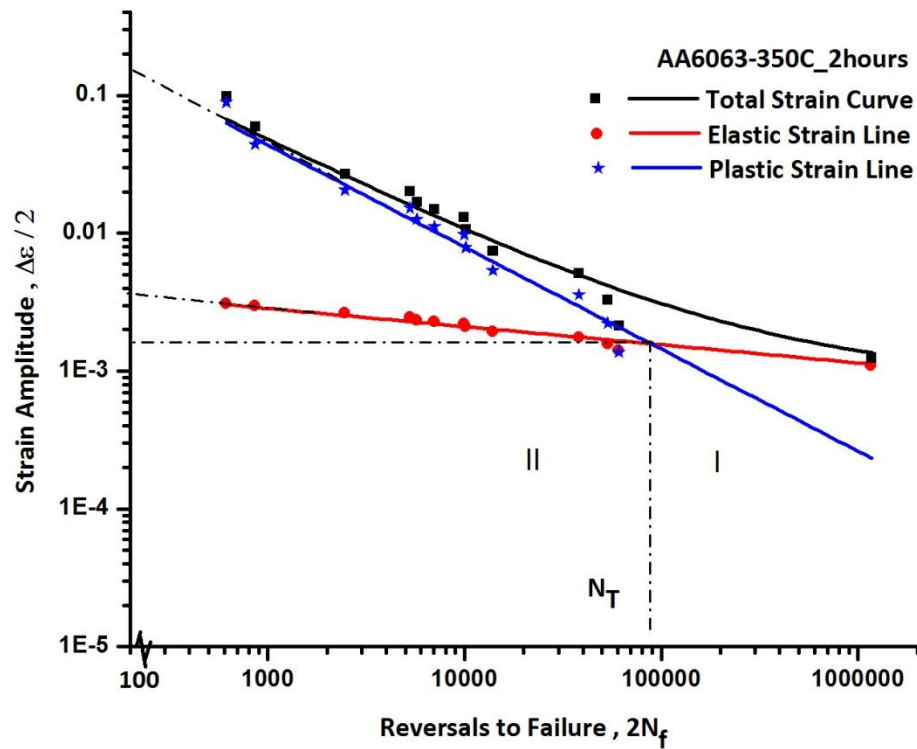


Fig. 5.14 Strain life curves for AA6063 alloy heat treated at 350°C with soaking time of 2hours

In a similar way the low cycle fatigue data for other cases of soaking time i.e. 4 hours, 6 hours and 8 hours are given in Tables 5.7, 5.8 and 5.9, respectively. The strain-life relations for these three cases are plotted in Figs. 5.15, 5.16 and 5.17, respectively. Figure 5.18 elaborates total strain-life curves for as received AA6063, heat treated AA6063 samples at 350°C with soaking times of 2hours, 4hours, 6 hours and 8hours for low cycle fatigue test. The comparison shows that heat treated sample at 350°C for 6hours of soaking time is having maximum transition fatigue life. The comparison of different fatigue parameters viz. ϵ'_f , σ'_f/E , b , c , n' , K' and N_T are shown in Table 5.10 for different soaking time cases at same heat treatment temperature of 350°C.

Table 5.7 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 350°C and with soaking time of 4 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
501314	5.16E-4	0	5.16E-04
215801	0.00122	0.00543	0.00665
59851	0.00131	0.00711	0.00842
50235	0.00137	0.00838	0.00975
48186	0.00147	0.01964	0.02111
17595	0.00168	0.01773	0.01941
16715	0.00176	0.02096	0.02272
16514	0.00183	0.02424	0.02607
13566	0.00193	0.02945	0.03138
13290	0.00201	0.03423	0.03624
6832	0.00219	0.04888	0.05107
3315	0.00228	0.05409	0.05637
1012	0.00236	0.06411	0.06647

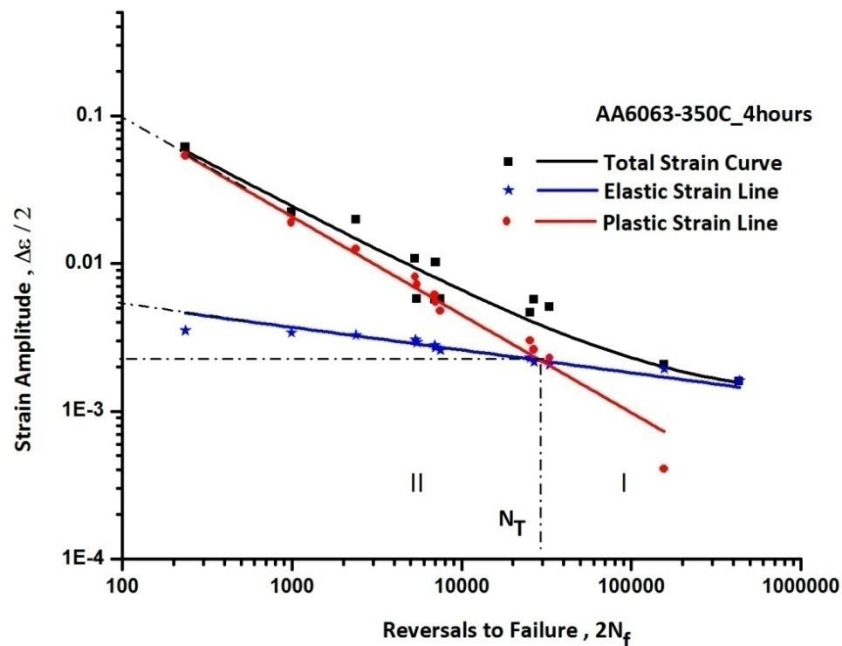


Fig. 5.15 Strain life curves for AA6063 alloy heat treated at 350°C with soaking time of 4 hours

Table 5.8 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 350°C and with soaking time of 6 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
999985	8.663E-4	0.0034	0.00427
290354	0.00113	0.00739	0.00852
35447	0.00133	0.01199	0.01332
33201	0.0014	0.01396	0.01536
18117	0.00149	0.01657	0.01806
11572	0.00158	0.01981	0.02139
8565	0.00167	0.02305	0.02472
8335	0.00176	0.02689	0.02865
6579	0.00186	0.03197	0.03383
4990	0.00194	0.03575	0.03769
3619	0.00225	0.04199	0.04424
1076	0.00281	0.0457	0.04851
819	0.00323	0.05366	0.05689

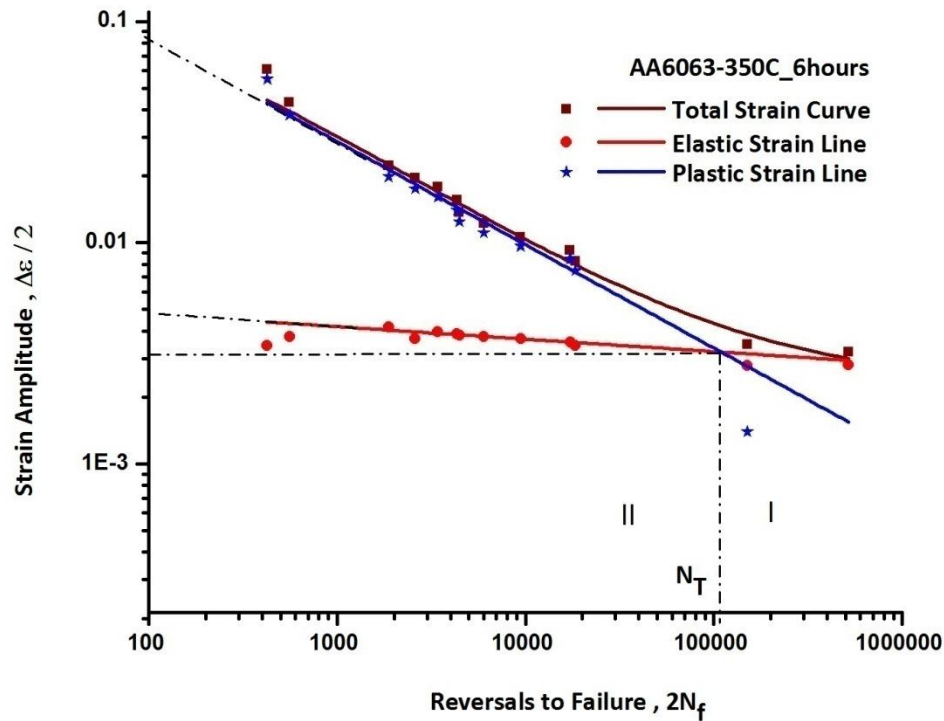


Fig. 5.16 Strain life curves for AA6063 alloy heat treated at 350°C with soaking time of 6hours

Table 5.9 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 350°C and with soaking time of 8 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
619041	0.0015	0.00255	0.00405
229002	0.0016	0.00388	0.00548
158571	0.00167	0.0045	0.00617
55914	0.00171	0.00586	0.00757
45276	0.00177	0.00687	0.00864
41485	0.00183	0.00709	0.00892
15140	0.00194	0.00833	0.01027
3890	0.00195	0.00965	0.0116
1230	0.00205	0.01121	0.01326
867	0.00214	0.01245	0.01459
601	0.00223	0.01672	0.01895
211	0.00231	0.01979	0.0221

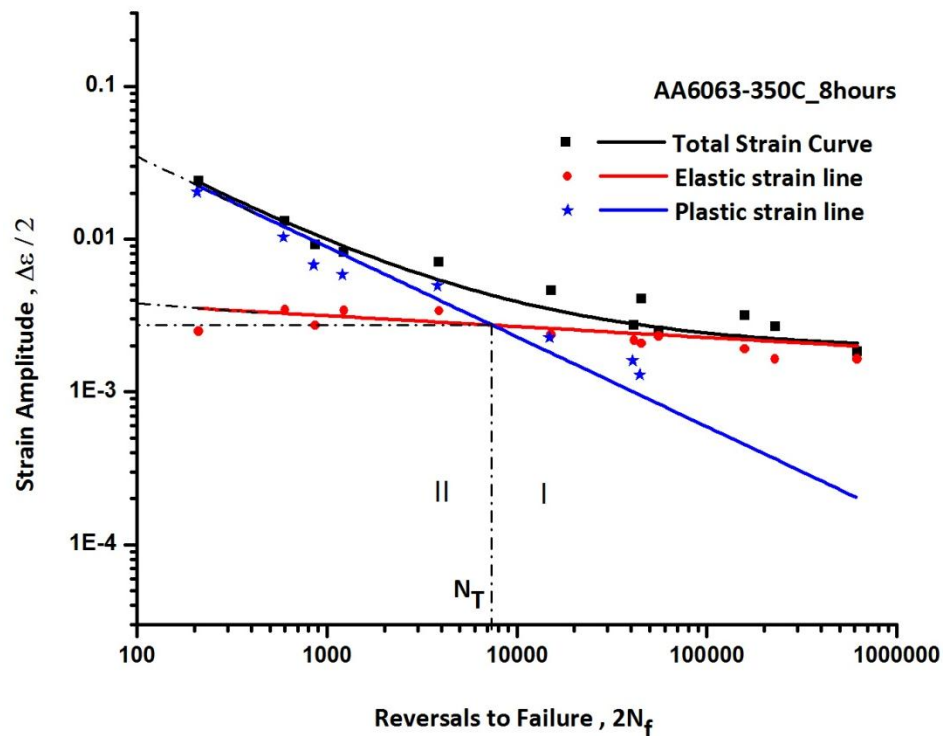


Fig. 5.17 Strain life curves for AA6063 alloy heat treated at 350°C with soaking time of 8 hours

Table 5.10 Low cycle fatigue parameters of aluminum alloy AA6063 at different soaking time and same heat treatment temperature of 350°C

6063 Alloy	Cyclic plastic strain (Fatigue Ductility coefficient) ϵ_f'	Cyclic elastic strain σ_f'/E	Fatigue Strength Coefficient σ_f' (MPa)	fatigue strength exponent b	fatigue ductility exponent c	cyclic strain hardening exponent n'	cyclic strength coefficient K' (MPa)	transition fatigue life N_T (cycles)
6063-T6	0.2915	0.006727	457.4	-0.165	-1.152	0.14322	545.7	632
6063-350°C_2hour	0.148	0.00379	227.4	-0.13	-0.6	0.216	343.56	87568
6063-350°C_4hour	0.09708	0.0051868	300.8	-0.07	-0.41	0.1707	447.89	29178
6063-350°C_6hour	0.08542	0.004766	271.66	-0.067	-0.65	0.10307	350.06	109786
6063-350°C_8hour	0.04019	0.007144	392.9	-0.070	-0.45	0.1555	647.65	7340

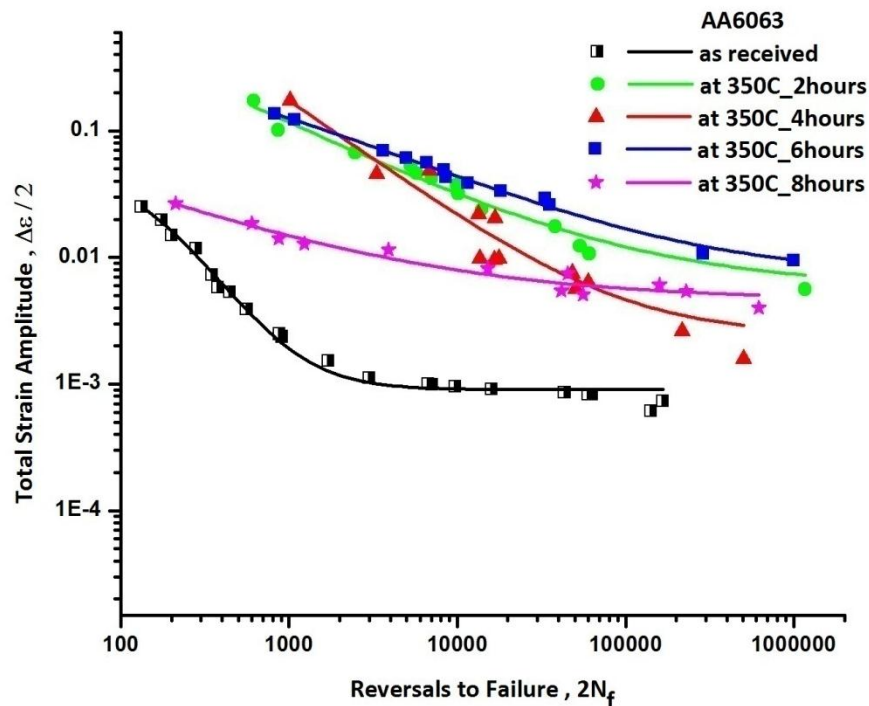


Fig. 5.18 Total strain – life curves for AA6063 samples with different soaking time and at same heat treatment temperature of 350°C

Figures 5.19 shows variation of cyclic plastic strain and fatigue strength coefficient with respect to soaking time. Cyclic strength coefficient and cyclic strain exponent variations with respect to soaking time is shown in Fig. 5.20. Variation of transition life with soaking is shown in Fig. 5.21. It can be observed from this figure that transition fatigue life is maximum at 6 hours of soaking time while it is increasing till 6 hours of soaking time and thereafter it decreases. Figure 5.22 demonstrates the variation of fatigue strength exponent and fatigue ductility exponent with soaking time.

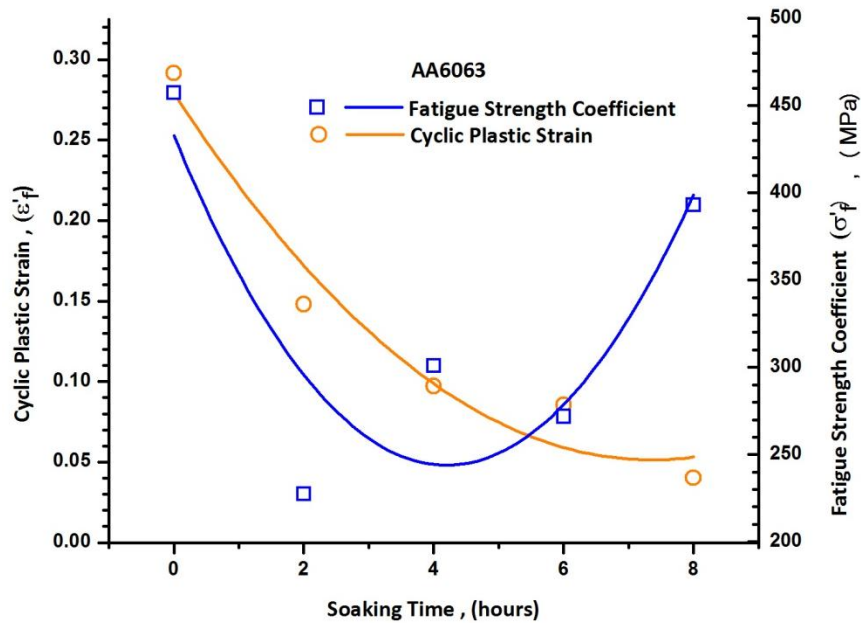


Fig. 5.19 Variation of fatigue Strength Coefficient (σ'_f) and cyclic plastic strain (ϵ'_p) with different soaking time at same heat treatment temperature of 350°C

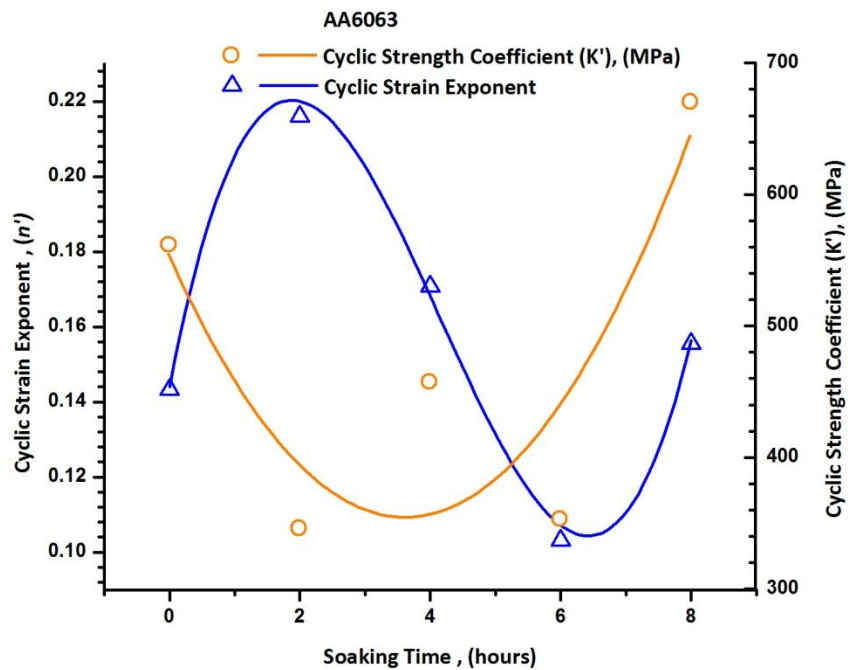


Fig. 5.20 Variations of cyclic Strain Hardening Exponent, (n') and strength coefficient (K') with different soaking time at same heat treatment temperature of 350°C

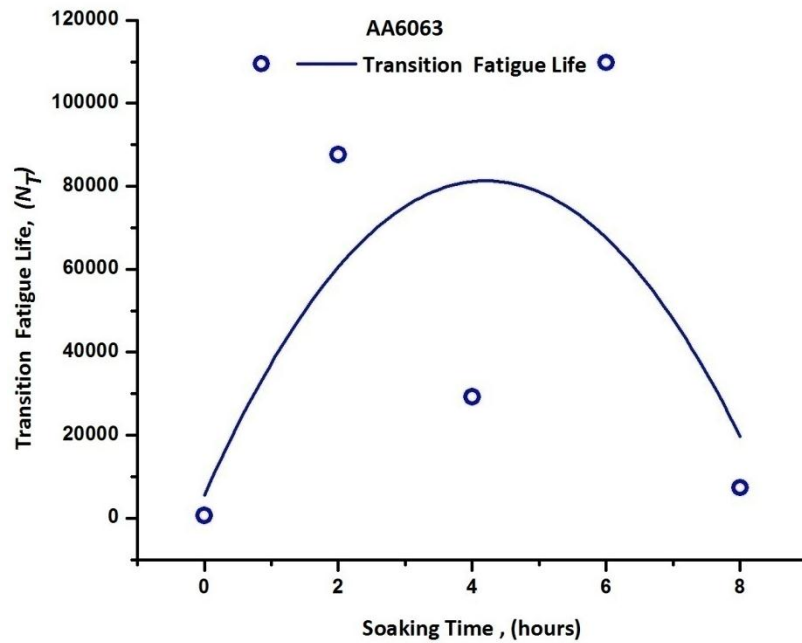


Fig. 5.21 Variation of transition fatigue life (N_T) with different soaking time at same heat treatment temperature of 350°C

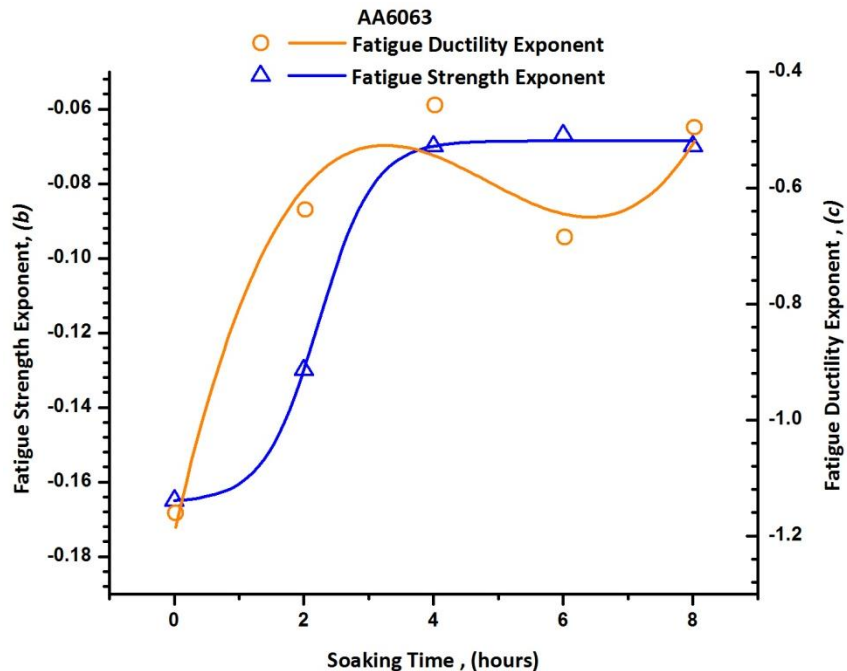


Fig. 5.22 Variations of fatigue Strength Exponent (b) and Fatigue Ductility Exponent (c) with different soaking time at same heat treatment temperature of 350°C

It is also observed from Table 5.11 and Table 5.12 that empirical prediction for elastic strain is not good enough by SWT method while that of plastic strain is satisfactory. Prediction for elastic and plastic strain by Morrows method is very good.

Table 5.11 Comparison of experimental, numerical and empirical results for elastic strain for AA6063 at different soaking times for same heat treatment temperature of 350°C

Condition	Force (N)	Cycles	Elastic Strain						
			Exp.	FEM	% Diff.	SWT	% Diff.	Morrow	% Diff.
6063-350°C_4hour	65	1012	0.00236	0.0022598	4.24	0.01361	82.66	0.005674	58.4
6063-350°C_6hour	60	819	0.00323	0.0028914	10.49	0.006578	50.8	0.003836	18.76
6063-350°C_8hour	60	211	0.00231	0.0025226	9.2	0.010718	78.4	0.004978	53.5

Table 5.12 Comparison of experimental, numerical and empirical results for Plastic strain for AA6063 at different soaking times for same heat treatment temperature of 350°C

Condition	Force (N)	Cycles	Plastic Strain						
			Exp.	FEM	% Diff.	SWT	% Diff.	Morrow	% Diff.
6063-350°C_4hour	65	1012	0.06411	0.056009	12.6	0.05358	16.425	0.022337	65.158
6063-350°C_6hour	60	819	0.05366	0.054729	1.99	0.005061	90.69	0.002951	94.5
6063-350°C_8hour	60	211	0.01979	0.021745	9.8	0.008272	58.232	0.003842	80.589

Figures 5.23, 5.24 and 5.25 illustrate variation of elastic and plastic strains over time at a particular node on the surface of the specimen along the fracture cross-section. It is observed from the figure that plastic strain is constant over time while elastic strain varies between maximum value of 0.00225965 and minimum value of 0.00158233 for heat treatment temperature of 350 °C and 4hours of soaking time, maximum value of 0.0029131 and minimum value of 0.00215288 heat treatment temperature of 350°C and

6hours of soaking time and maximum value of 0.00252262 and minimum value of 0.00190218 for heat treatment temperature of 350°C and 8hours of soaking time.

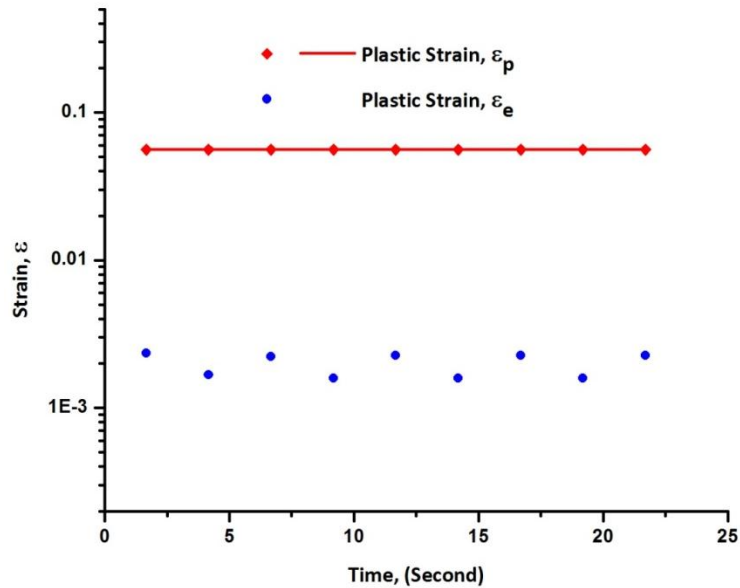


Fig. 5.23 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 350°C and 4hours of soaking time

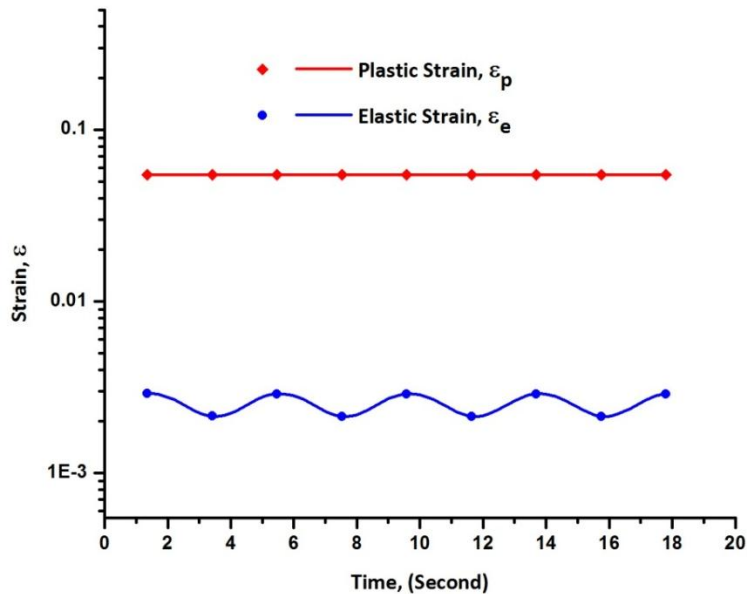


Fig. 5.24 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 350°C and 6hours of soaking time

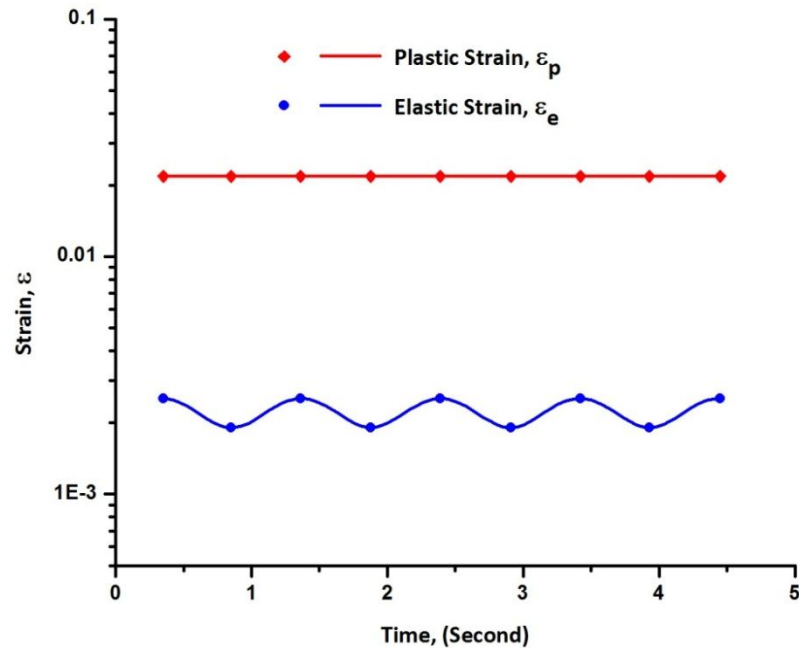


Fig. 5.25 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 350°C and 8 hours of soaking time

Figures 5.26 and 5.27 show deformed shape of the specimen heat treated at 350°C and soaked for 4 hours at a particular instant of time with elastic and plastic strain distributions, respectively. And Figures 5.28 and 5.29 show deformed shape of the specimen heat treated at 350°C and soaked for 6 hours at a particular instant of time with elastic and plastic strain distributions, respectively. Also Figs. 5.30 and 5.31 show deformed shape of the specimen heat treated at 350°C and soaked for 8 hours at a particular instant of time with elastic and plastic strain distributions, respectively.

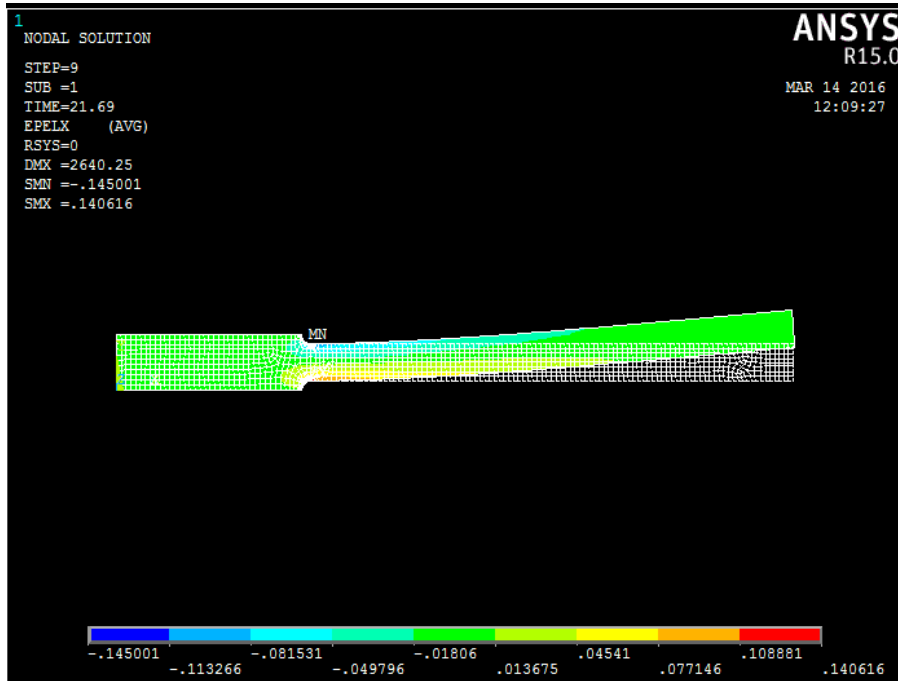


Fig. 5.26 Elastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 4hour

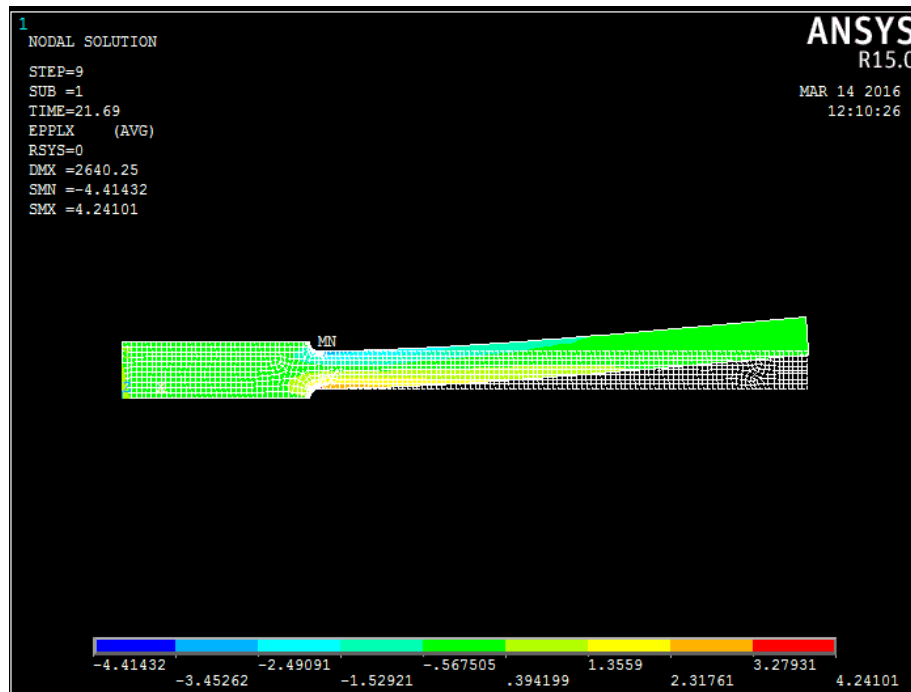


Fig. 5.27 Plastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 4hours

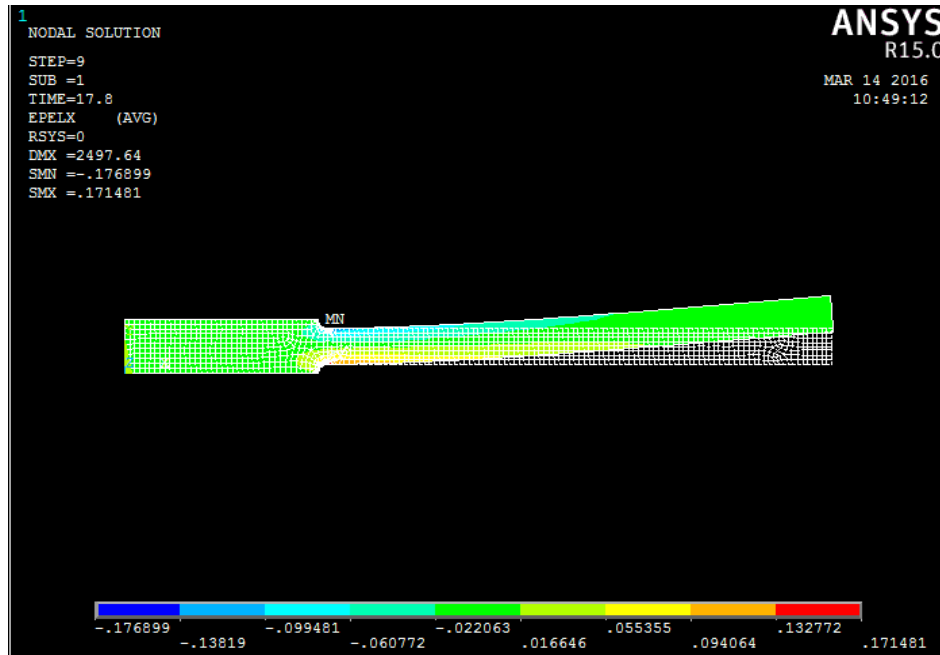


Fig. 5.28 Elastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 6hours

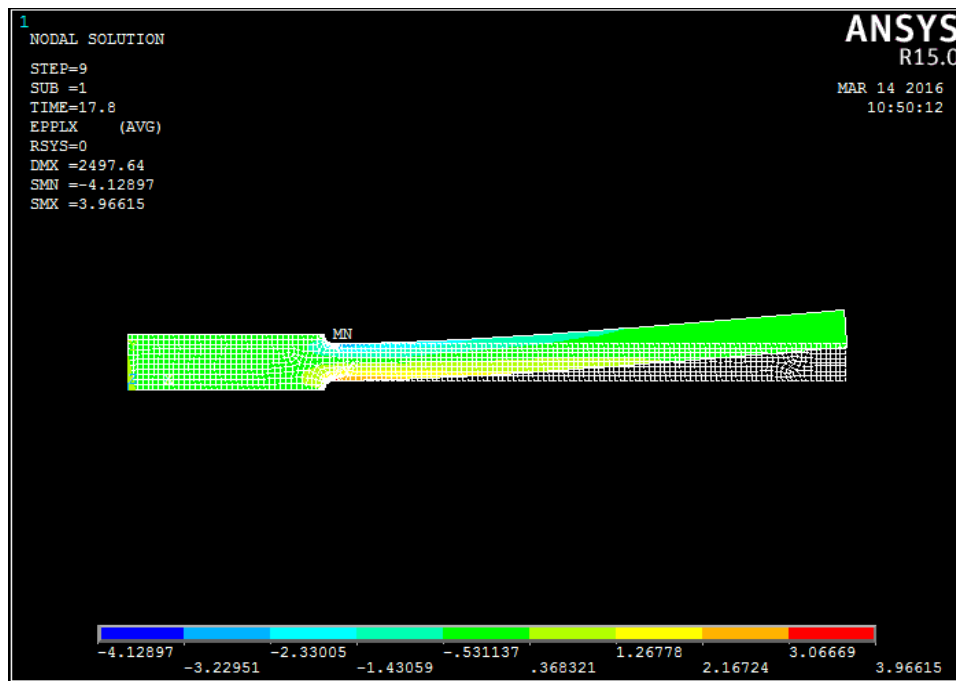


Fig. 5.29 Plastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 6hours

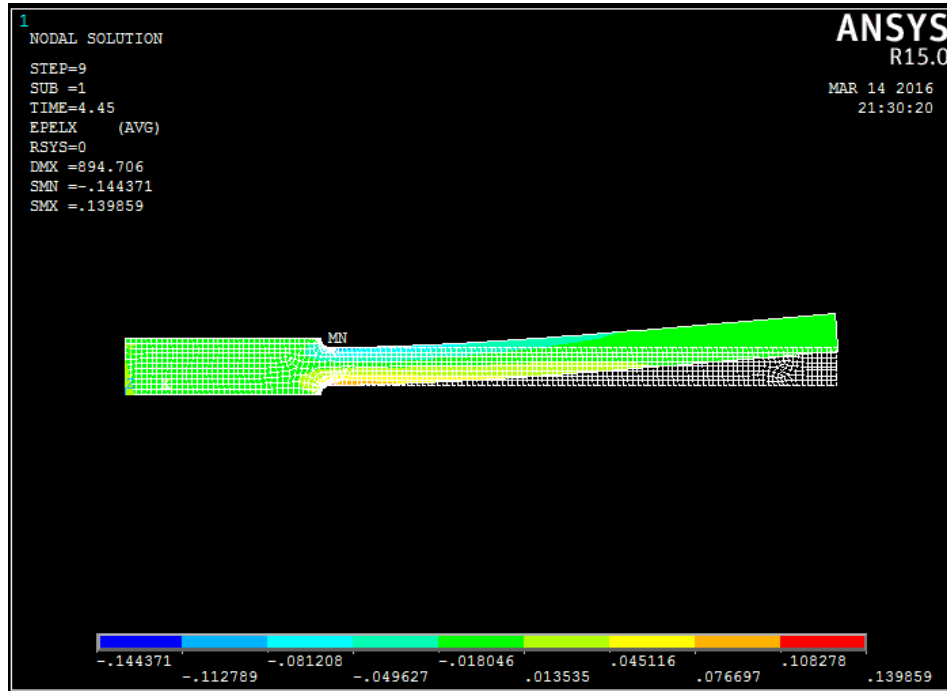


Fig. 5.30 Elastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 8hours

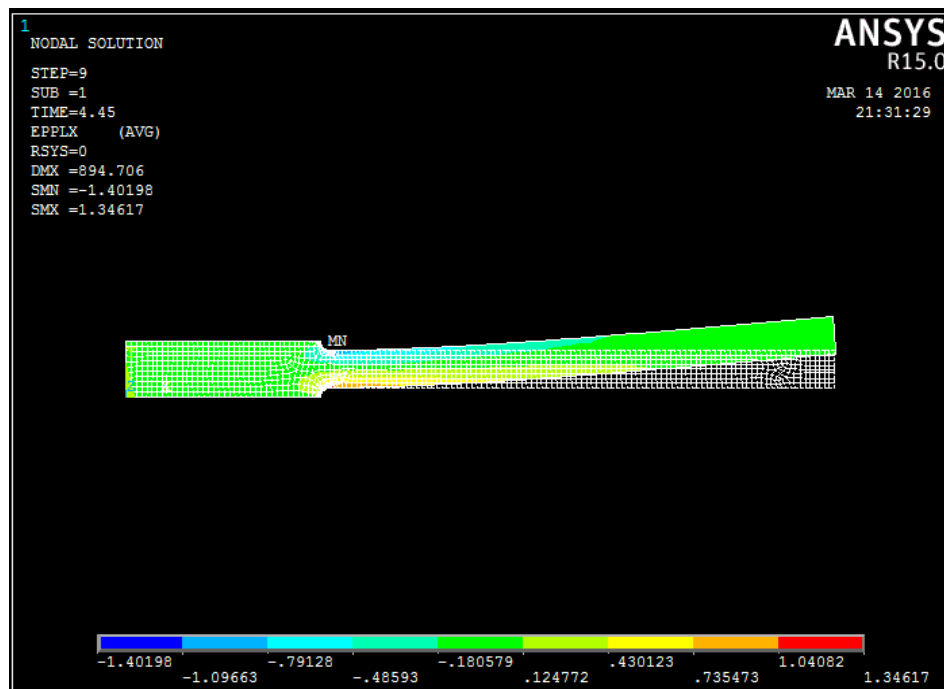


Fig. 5.31 Plastic strain at particular time on deformed shape for AA6063 heat treated at 350°C and soaked for 8hours

Figures 5.32, 5.33 and 5.34 demonstrate fitted lines for strain-life data by experimental method, least square analysis, regression for model I and model II for AA6063 samples heat treated at 350°C and soaked for 4hours for elastic, plastic and total strains, respectively. Similarly Figs. 5.35, 5.36, 5.37, 5.38, 5.39 and 5.40 show fitting of AA6063 samples heat treated at 350°C and soaked for 4hours and 8hours for elastic, plastic and total strain-life data by experimental, least square, regression model I and model II. Different lines show good fitting as points lie evenly above and below each line. It is observed from these figures that for all cases fitting with regression model II follows experimental fitting closely.

Table 5.13 shows values of R^2 and modified R^2 for elastic, plastic and total strain data.

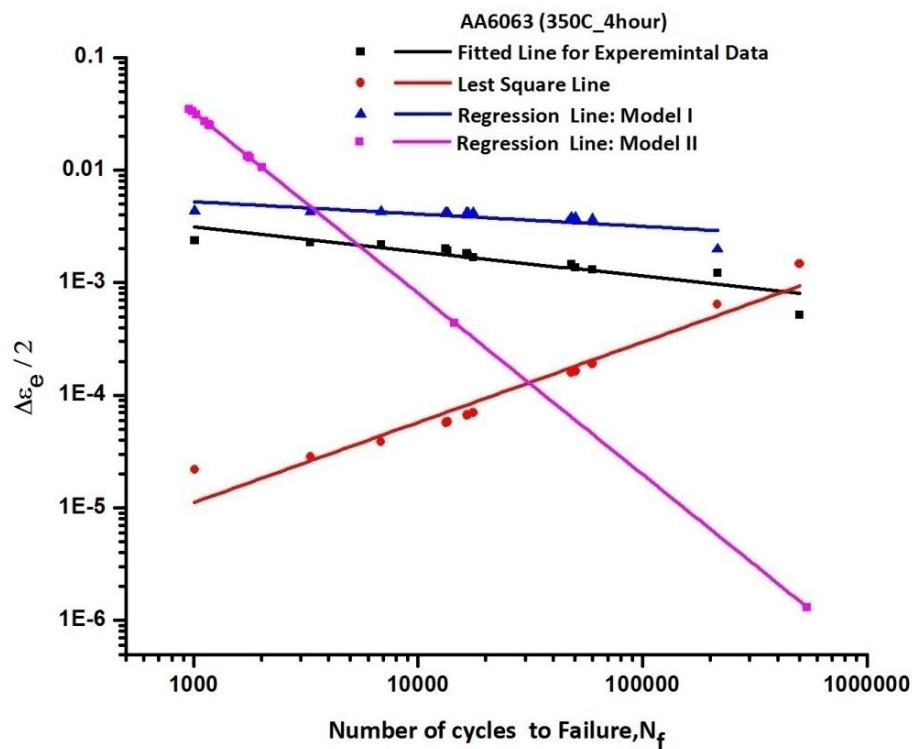


Fig. 5.32 Fitted elastic strain lines for AA6063 heat treated at 350°C and soaked for 4hours

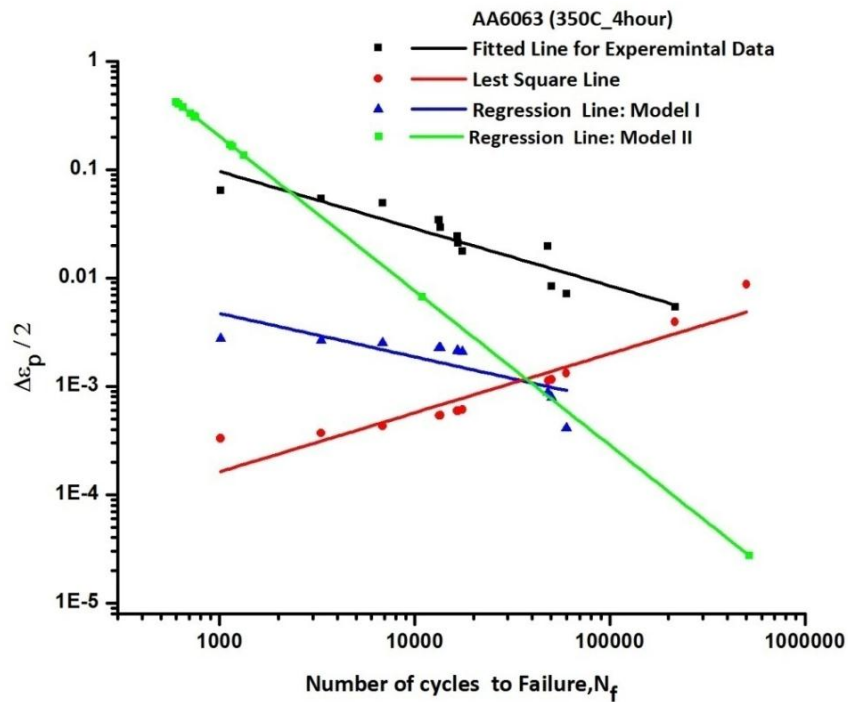


Fig. 5.33 Fitted plastic strain lines for AA6063 heat treated at 350°C and soaked for 4hours

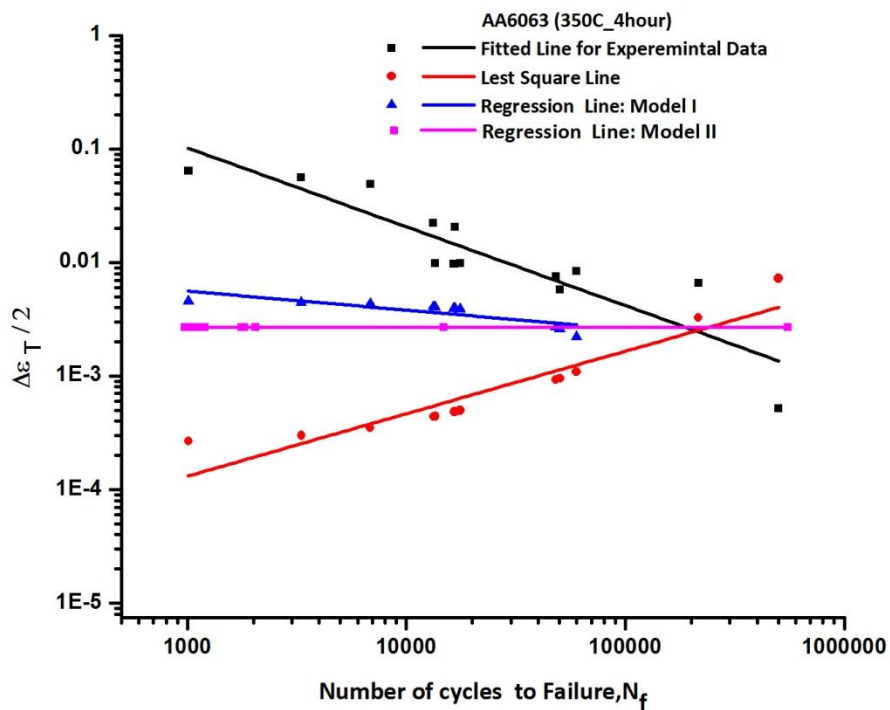


Fig. 5.34 Fitted total strain lines for AA6063 heat treated at 350°C and soaked for 4hours

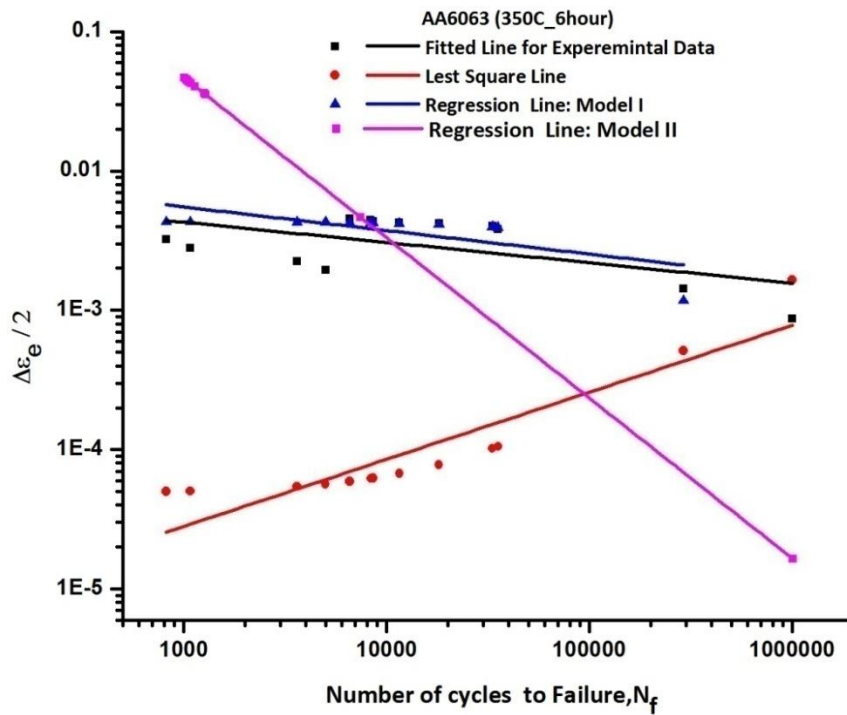


Fig. 4.35 Fitted elastic strain lines for AA6063 heat treated at 350°C and soaked for 6hours

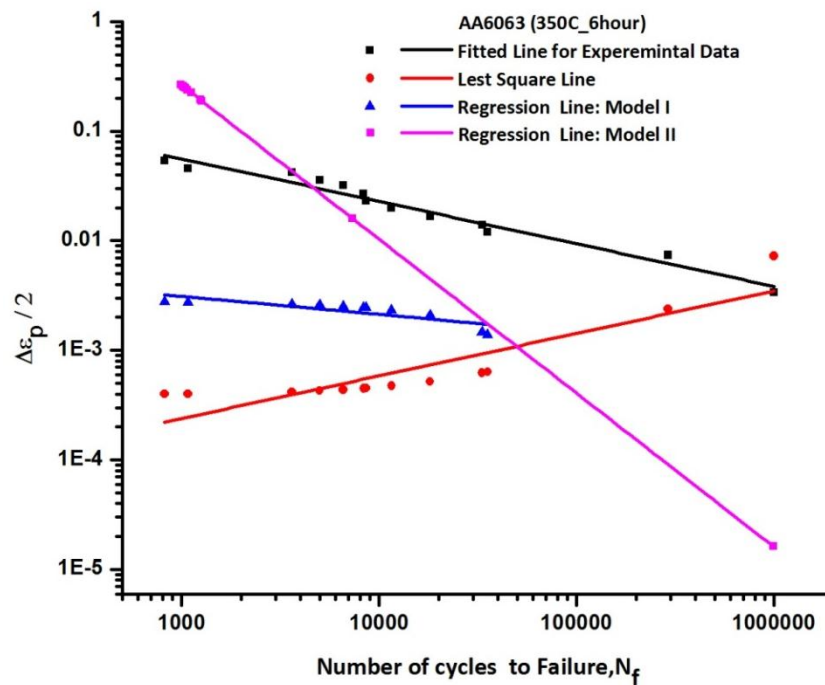


Fig. 5.36 Fitted plastic strain lines for AA6063 heat treated at 350°C and soaked for 6hours

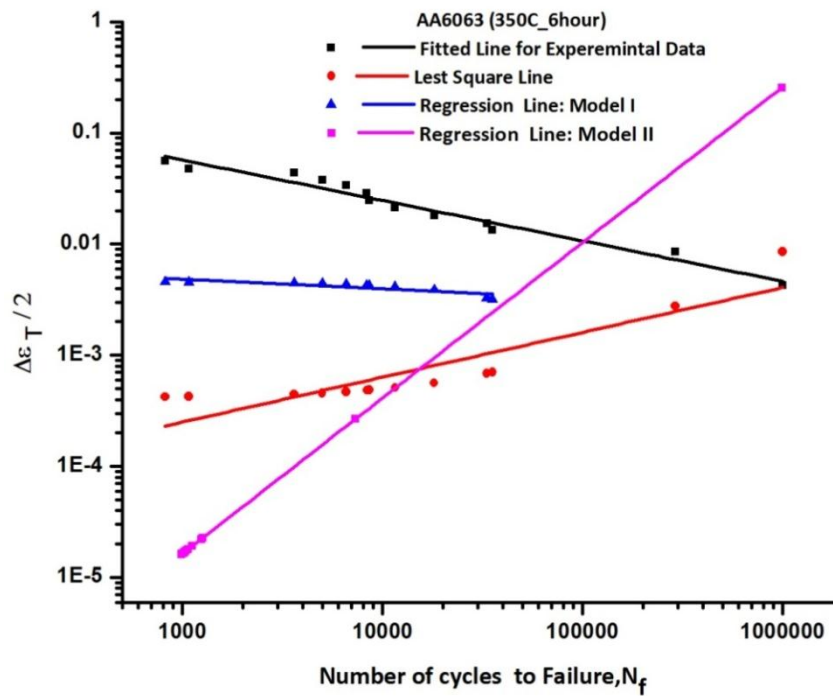


Fig. 5.37 Fitted total strain lines for AA6063 heat treated at 350°C and soaked for 6hours

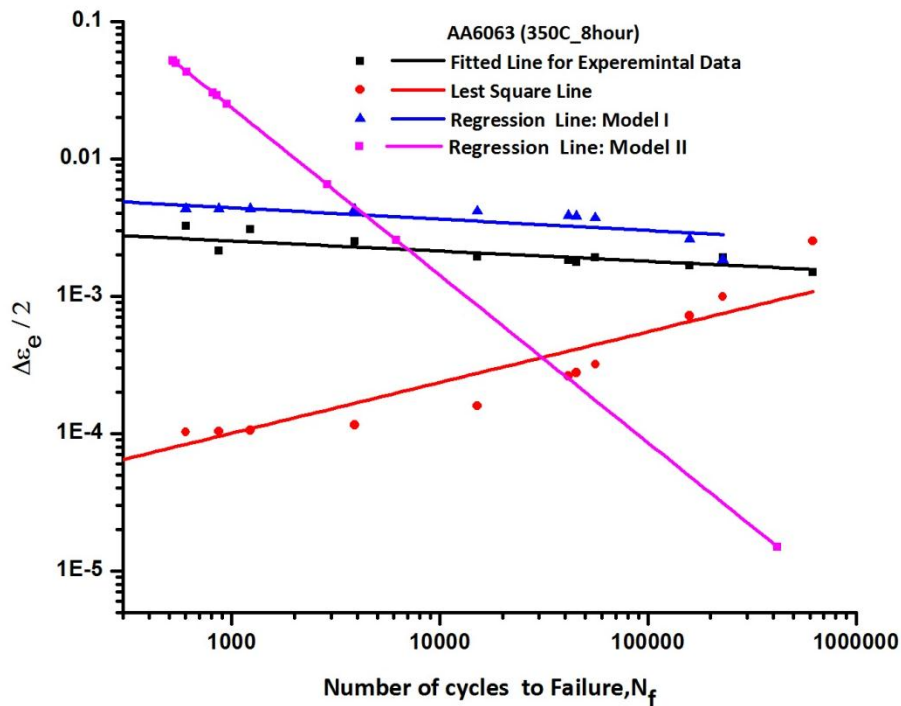


Fig. 5.38 Fitted elastic strain lines for AA6063 heat treated at 350°C and soaked for 8hours

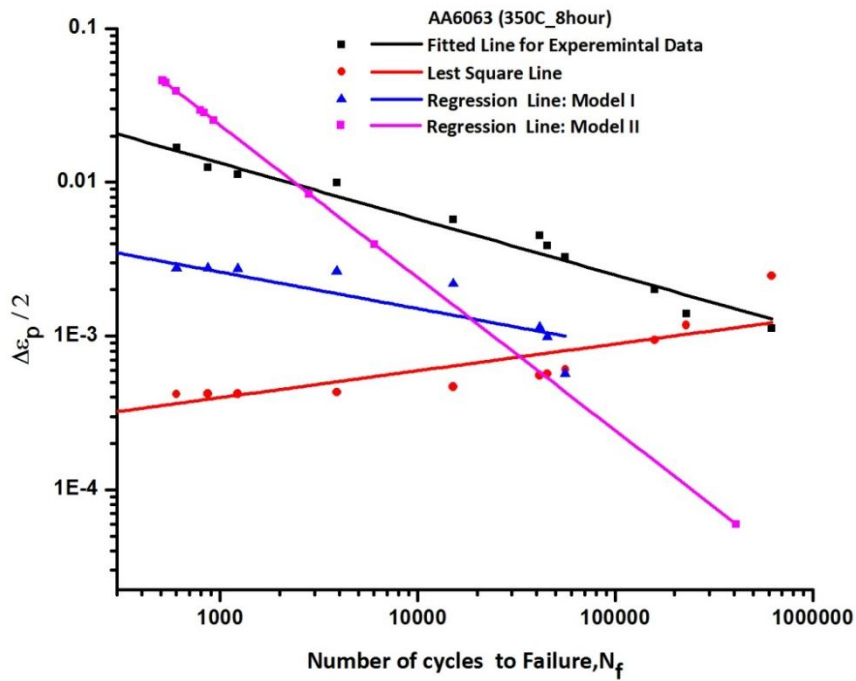


Fig. 5.39 Fitted plastic strain lines for AA6063 heat treated at 350°C and soaked for 8hours

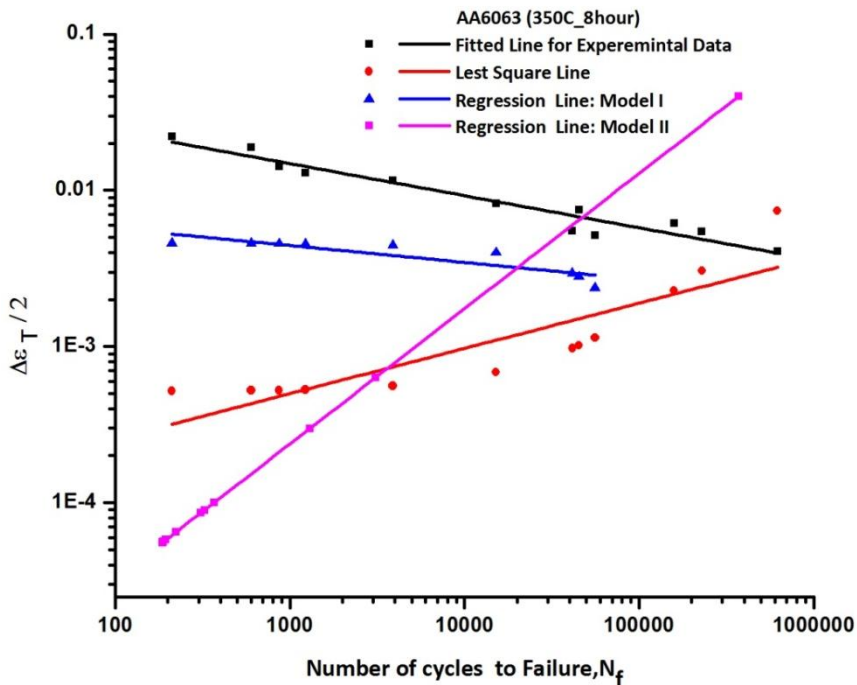


Fig. 5.40 Fitted total strain lines for AA6063 heat treated at 350°C and soaked for 8hours

Table 5.13 R² and modified R² values for elastic , plastic and total strain for AA6063 with different soaking time and at same heat treatment temperature of 350°C

Condition	Parameters	Elastic Strain	Plastic Strain	Total Strain
AA6063-T6 as received	R ²	1.9722	0.14756	0.013728
	Mod. R ²	-3.1871	-5.1078	-5.2487
AA6063-350C_2hour	R ²	3.5747	0.14449	0.20151
	Mod. R ²	-5.1912	-8.9333	-8.8711
AA6063-350C_4hour	R ²	6.4776	0.65131	0.543
	Mod. R ²	-2.0244	-8.3804	-8.4985
AA6063-350C_6hour	R ²	1.7989	0.45495	0.57194
	Mod. R ²	-7.1284	-8.5946	-8.467
AA6063-350C_8hour	R ²	12.634	0.46144	3.7013
	Mod. R ²	3.8972	-9.4924	-5.9286

Figures 5.41 to 5.43 explain how SWT parameter remain constant for AA6063 alloy heat treated at 350°C and soaked for 4hours, 6hours and 8hours, respectively, for rotating bending LCF data.

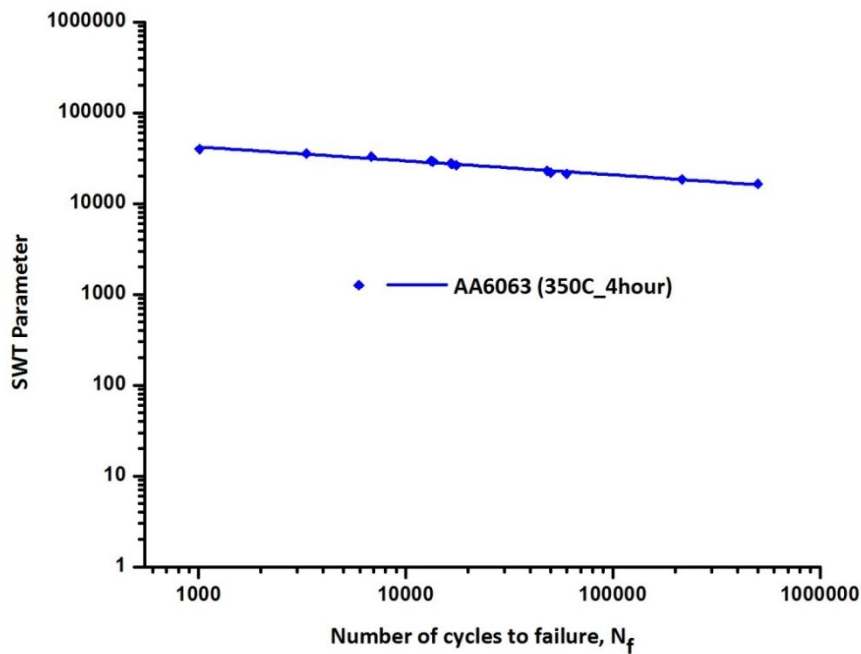


Fig. 5.41 Variation of SWT parameter with number of cycles to failure for AA6063 heat treated at 350°C and soaked for 4hours

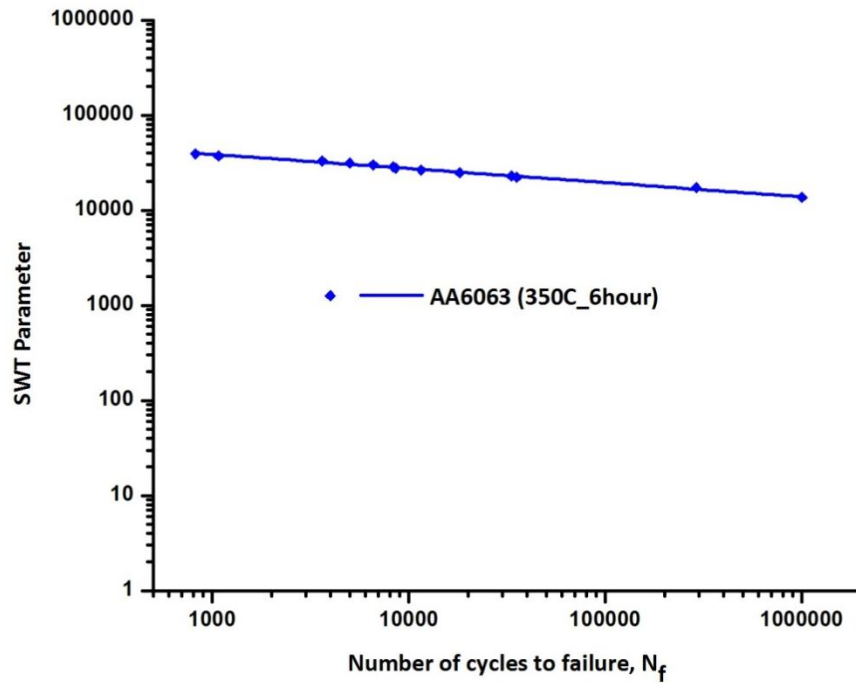


Fig. 5.42 Variation of SWT parameter with number of cycles to failure for AA6063 heat treated at 350°C and soaked for 6hours

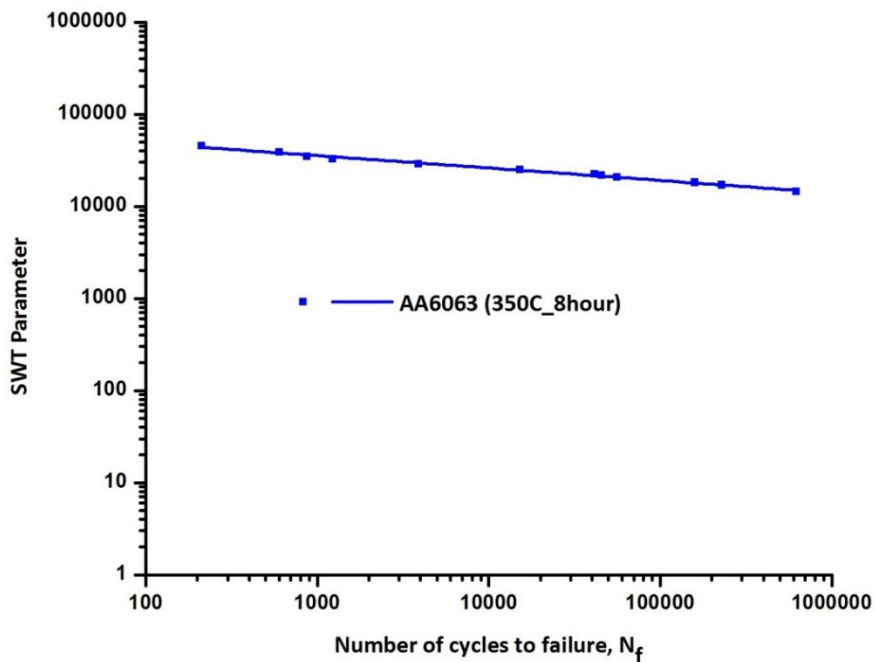


Fig. 5.43 Variation of SWT parameter with number of cycles to failure for AA6063 heat treated at 350°C and soaked for 8hours

5.3 Conclusion

Following observation are made from the analysis of present chapter

1. Yield strength and maximum stress continuously decrease with the increasing soaking time at the same heat treatment temperature of 350 °C. Percentage elongation has a increasing tendency with increase in soaking time.
2. Strain Hardening exponent (n) is asymptotically increasing with increase in soaking time while strength Coefficient (K) initially decreased with increase in soaking time and after certain soaking time it again increased.
3. Shear modulus (G) has a decreasing tendency with increase in soaking time.
4. Fatigue strength co-efficient (σ_f') asymptotically increased with increase in soaking time while cyclic plastic strain (ϵ_f') initially increased and then decreased with increase in soaking time.
5. Cyclic strength co-efficient (K') has a increasing tendency with increase in soaking time.
6. Cyclic strain exponent (n') initially increased and then decreased with increase in soaking time.
7. Transition fatigue life (N_T) initially increases and then decreases with increasing soaking time.
8. Fatigue ductility exponent (c) has an increasing tendency with increasing in soaking time.
9. Fatigue strength exponent (b) has initially decreasing tendency and after that increasing tendency with increasing in soaking time.
10. Experimental strain values closely follow to that obtained numerically.