Chapter 4

Low Cycle Fatigue Behaviour of Aluminum alloy AA6063 at Elevated Temperatures

4.1 Introduction

The effect of temperature on tensile and fatigue properties of an aluminium alloy AA6063 at different temperature are studied. The observations are made with different heat treatment temperatures ranging from 100℃ to 500℃ at constant strain rate of $2\times10^{-3}S^{-1}$. It is observed that the yield stress and ultimate tensile strength continuously decreased with increase in temperature. The strain hardening exponent ***n*** inially decreases but after certain temperature increases and strength hardening coefficient ***K*** decreases asymptotically when the temperature increased. Fatigue parameters and transition fatigue life (N_T) are observed at different temperatures with same soaking time.

4.2 Results

Tensile tests were carried out for samples heat treated at various temperatures, ranging from room temperature to 350℃ with soaking time of 2hour and water solution treatment. Tensile engineering stress-strain curves of the alloy AA6063 for different heat treatment temperatures are shown in Figs. 4.1- 4.3**.** Table 4.1 shows values of n, σ_{frac}^{Eng}, K, σ_{frac}^{true} , σ_y , σ_{max} , ε_{fract} , E, , for as received AA6063 and samples of AA6063 under different heat treatment temperatures Viz. 100℃, 200℃, 350℃ for 2 hour soaking time.

True plastic stress versus true plastic strain is plotted in log-log scale for the samples as shown in Fig. 4.4 and n, K values are calculated for all cases and presented in

Table 4.1. It is observed that yield strength (0.2% offset) and maximum stress continuously decreased from as received (room temperature) to 350℃ heat treatment temperatures as shown Fig. 4.5. Figure 4.6 shows variation of strain at fracture with heat treatment temperature with constant soaking time.

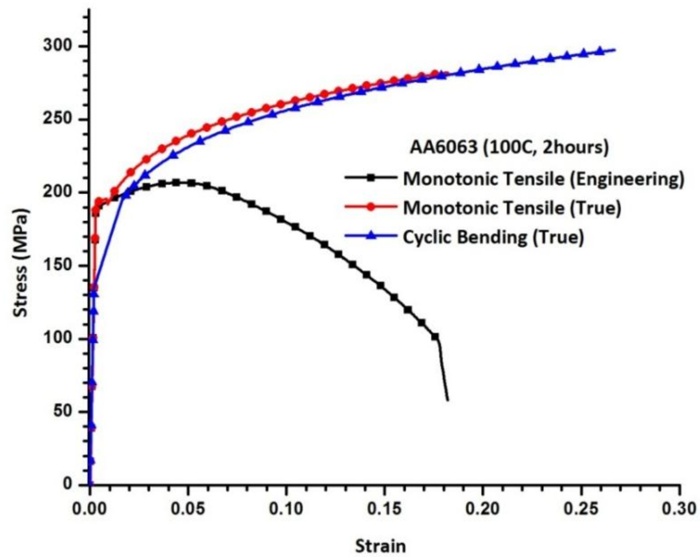

Fig. 4.1 Stress–strain curves for AA6063 alloy at 100℃ heat treatment with 2 hour soaking time

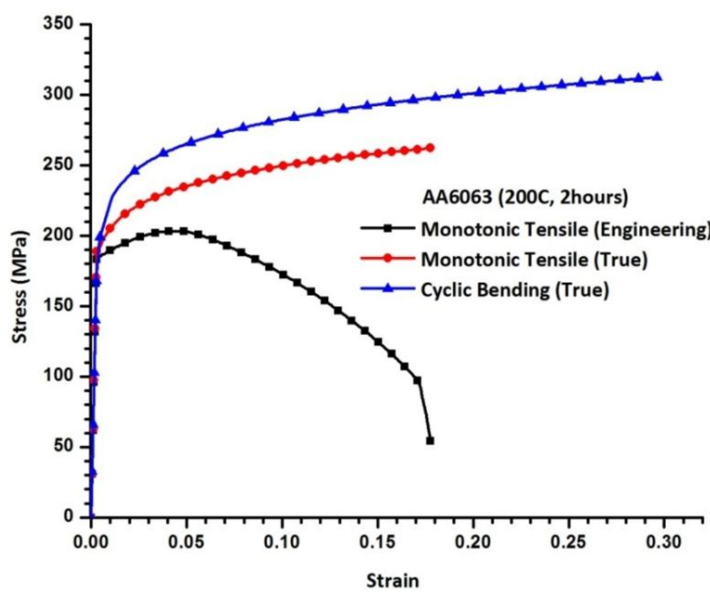

Fig. 4.2 Stress–strain curves for AA6063 alloy at 200℃ heat treatment with 2 hour soaking time

Table 4.2, 4.3 and 4.4 shows comparison of values of n, k and $\sigma_{fracture}^{true}$ obtained experimentally for the heat treatment cases (100℃, 200℃, 350℃) with 2 hour soaking time, respectively, to that obtained by empirical relations given by Eqs. (2.68) to (2.70).

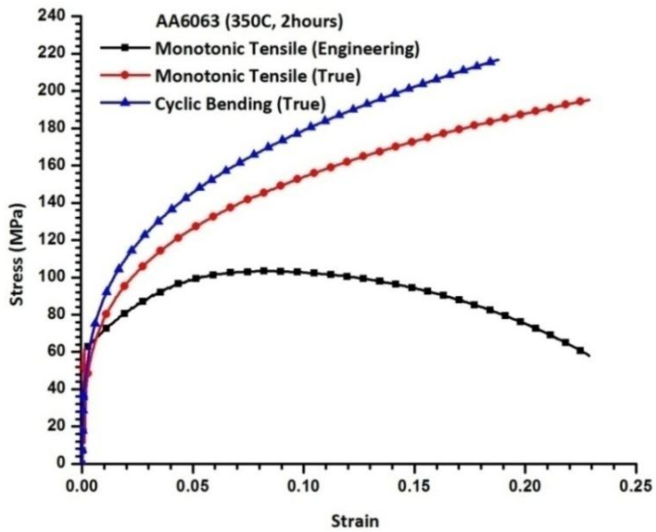

Fig. 4.3 Stress–strain curves for AA6063 alloy at 350℃ heat treatment with 2 hour soaking time

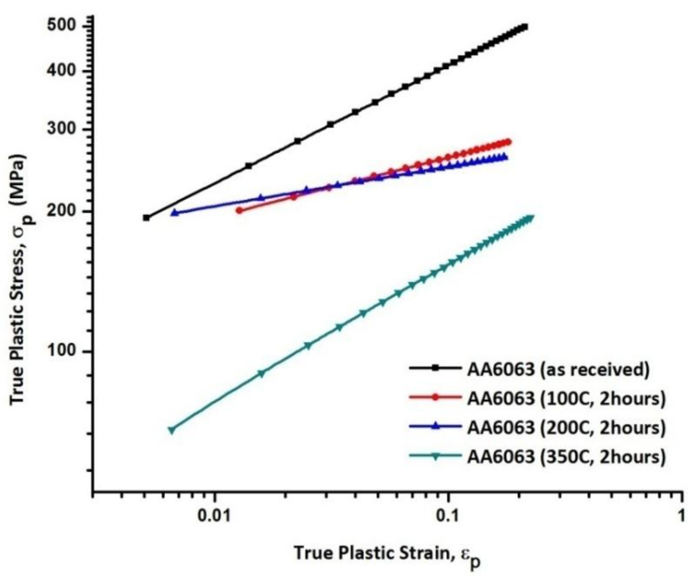

Fig. 4.4 Log-Log true plastic stress versus true plastic strain plot at different heat treatment temperatures with same soaking time

Table 4.1 The monotonic properties of AA6063 at different heat treatment temperatures with same soaking time

Conditions	n	σ_{frac}^{Eng}	K	$\sigma_{fracture}^{true}$	σ_y (MPa)	σ_{Max} (MPa)	$\varepsilon_{Frac.}$	E (GPa)
As Received	0.25	859.5	776.2	237.49	169.670	214.80	0.2745	68
100℃_2hr	0.137	368.77	350.75	246.01	193.522	214.07	0.257	65
200℃_2hr	0.083	352.18	341.9	227.08	184.500	212.80	0.240	62
350℃_2hr	0.28	398.4	338.8	345.91	60.060	117.30	0.294	60

Table 4.2 Comparison of values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 100℃ and soaked for 2 hours

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.137	0.12783	0.12528	0.14166
k	350.75	350.75	350.75	466.74
$\sigma_{fracture}^{true}$	246.01	282.11	313.42	346.14

Table 4.3 Comparison of values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 200℃ and soaked for 2 hours

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.083	0.082815	0.082999	0.085111
k	341.9	341.9	341.9	313.12
$\sigma_{fracture}^{true}$	227.08	296.32	341.66	262.21

Table 4.4 Comparison of values of n, k and $\sigma_{fracture}^{true}$ for AA6063 heat treated at 350℃ and soaked for 2 hours

Parameter	Experimental	Theoretical		
		Eq. (2.68)	Eq. (2.69)	Eq. (2.70)
n	0.28	0.33825	0.32183	0.28359
k	336.8	336.8	336.8	349.93
$\sigma_{fracture}^{true}$	345.91	205.49	411.2	195.27

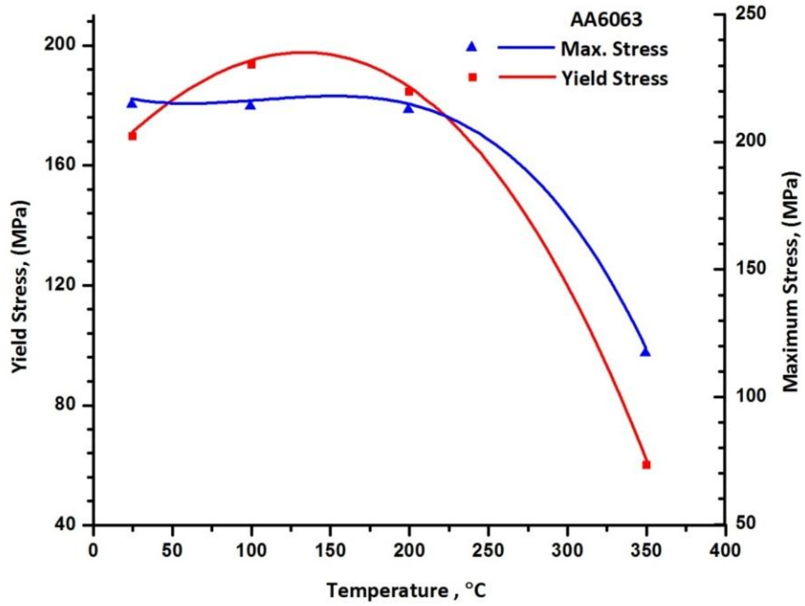

Fig. 4.5 Maximum Stress and Yield Stress variation with temperature for AA6063 alloy

Strain hardening exponent decreases with temperature, after certain temperature again increases as shown in Fig. 4.7. This figure also shows variation of strength coefficient which decreases asymptotically with increase in temperature. Highest value of 776.2MPa is observed for K in the case of as received condition.

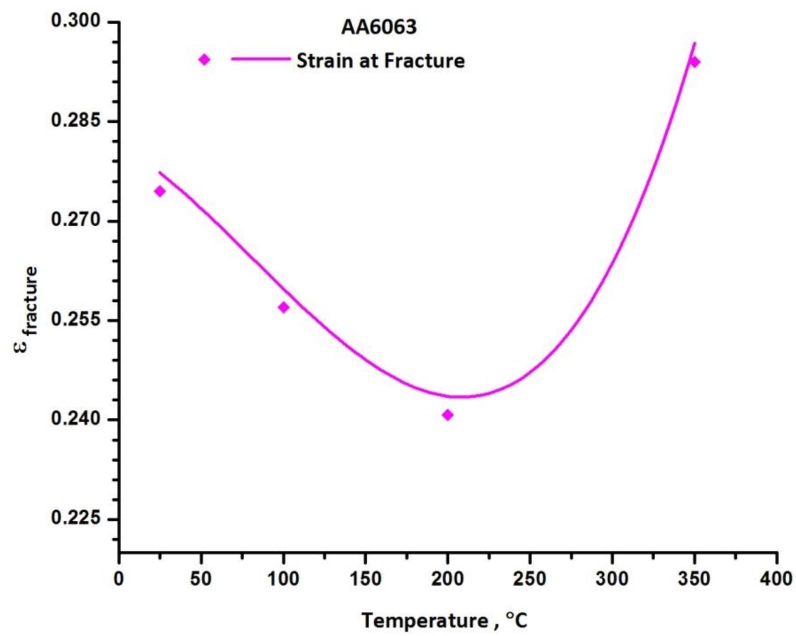

Fig. 4.6 Variation of Strain at fracture with different heat treatment temperature at same soaking time of 2 hour

Figure 4.8 shows cyclic bending true stress versus cyclic bending true strain curves for as received AA6063 and heat treated samples at 100℃, 200℃ and 350℃.

Torsion test results for the different heat treatment along with AA6063 at room temperature are shown in Fig. 4.9 . Different parameters obtained from torsion test are reported in Table 4.5 .

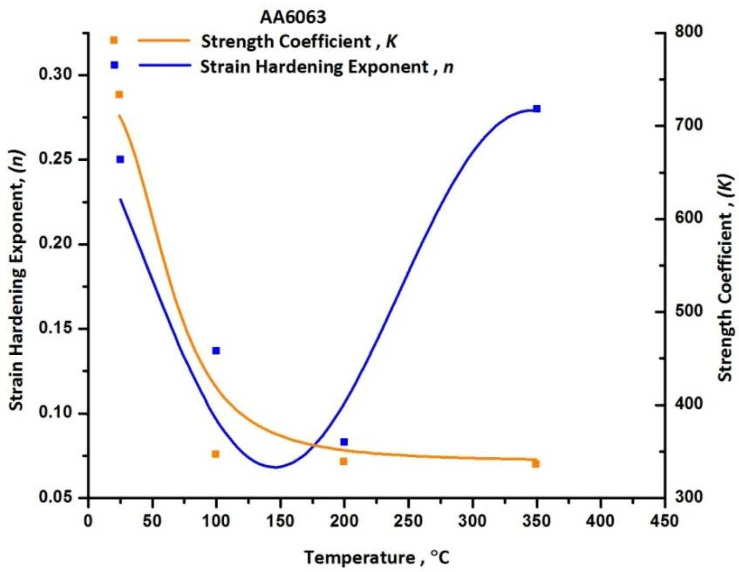

Fig. 4.7 Variation of strength Coefficient (K) and Strain Hardeningexponent (n) with heat treatment temperature at same soaking time

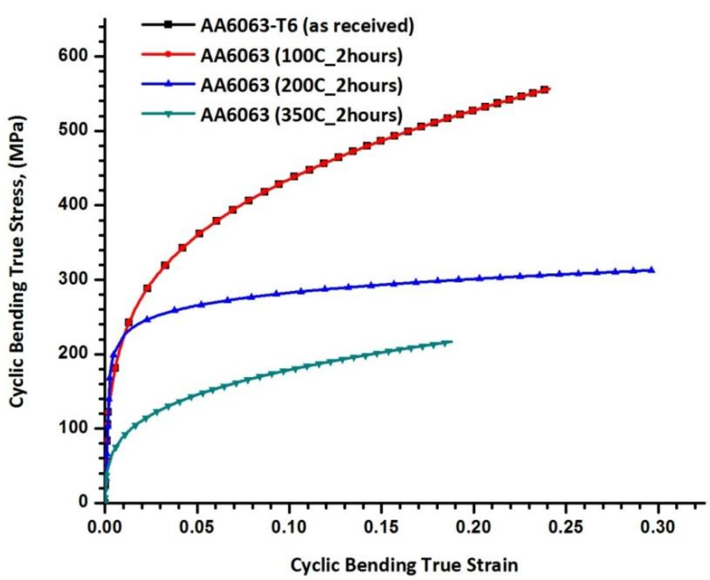

Fig. 4.8 Cyclic Bending True Stress-Strain Curves of AA6063 at various heat treatment temperatures with same soaking time

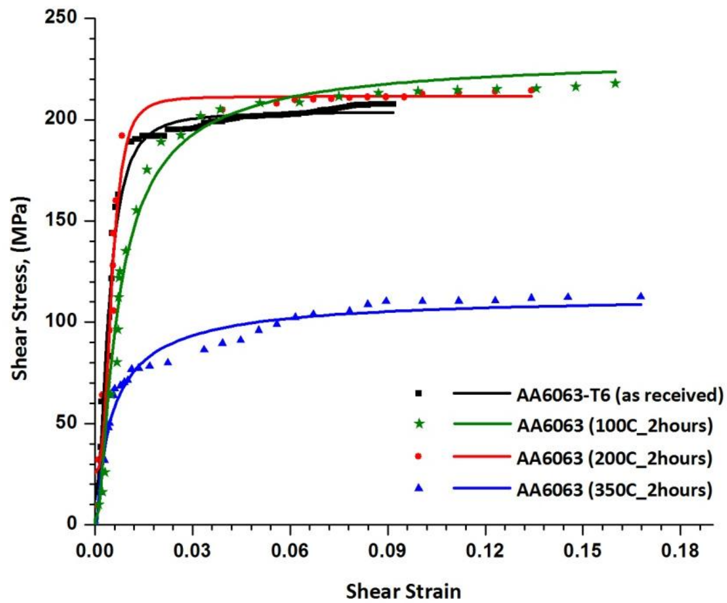

Fig. 4.9 Torsion curves for AA6063 for different heat treatment temperatures with same soaking time

Table 4.5 Torsion test data for AA6063 for different heat treatment temperatures with same soaking time

Parameters	symbol	As received	at 100C_2hr	at 200C_2hr	at 350C_2hr
Max. shear strain (Deg)	γ_{max}	6.4	8.97	7.69	9.61
Max. angle of twist (Deg)	α_{max}	100	140	120	150
Shear modulus (GPa)	G	25.9	24.22	23.3	22.3
Toughness (J/m³)	K_t	914	1373.6	1229.4	2276.4
Max. shear stress (MPa)	τ_{max}	209.03	21.33	213.2	115.112
Torque (Nm)	T_{max}	641.3	667.08	654.33	353.16

Figure 4.10 showed the variations of maximum shear strain and maximum angle of twist with heat treatment temperatures for AA6063. The maximum values for both are obtained at 350 ℃ heat treatment temperature and 2 hours soaking time condition. Variation of shear modulus and toughness with respect to heat treatment temperature is shown in Fig. 4.11. At higher heat treatment temperature shear modulus has a decreasing whereas toughness has a increasing tendency.

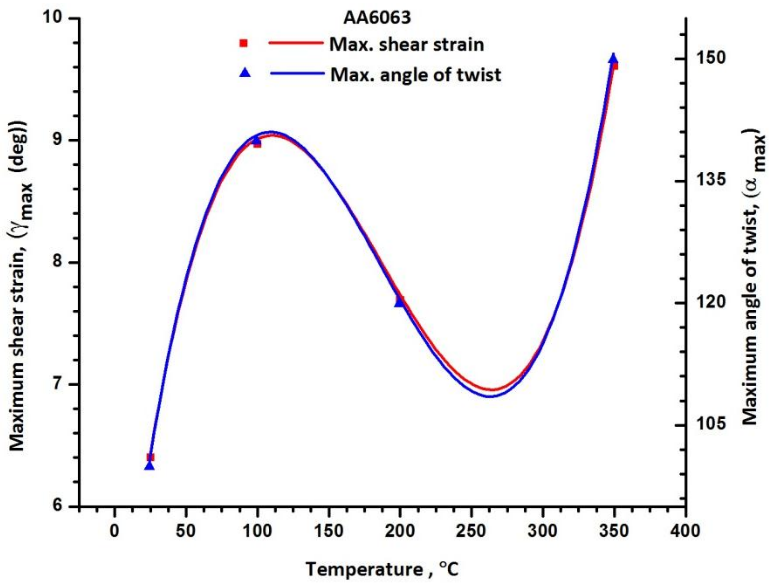

Fig. 4.10 Variation of maximum shear strain and maximum angle of twist with the different heat treatment temperatures at same soaking time

Both maximum shear stress and maximum torque have a decreasing tendency at higher temperature as illustrated in Fig. 4.12 .

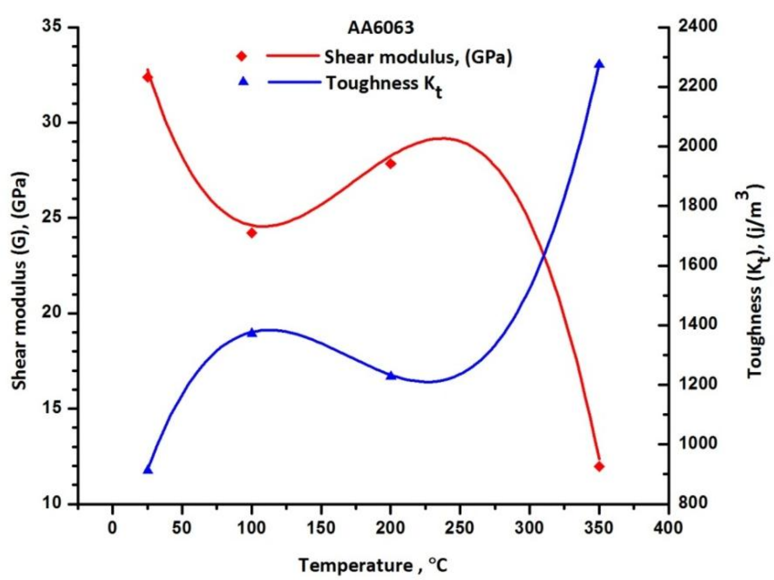

Fig. 4.11 Variation of shear modulus and toughness with the different heat treatment temperatures at same soaking time

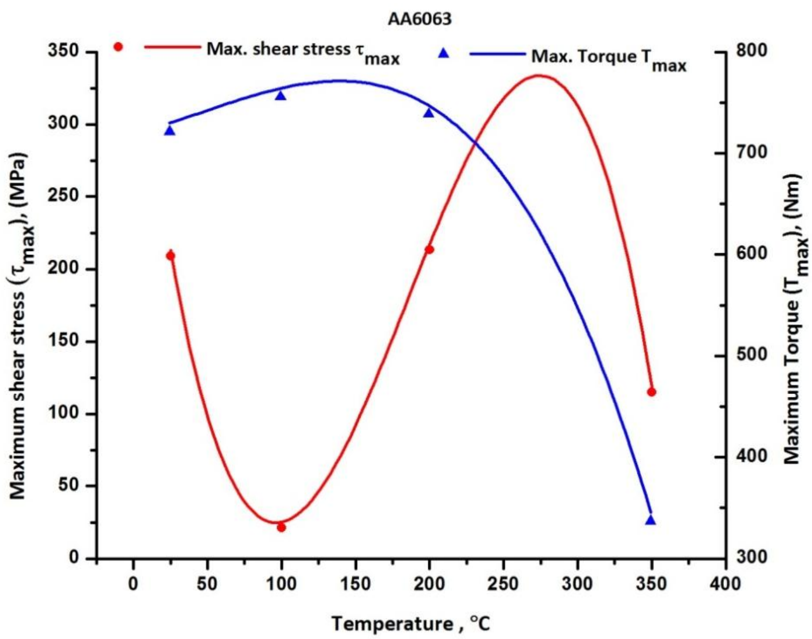

Fig. 4.12 Variation of maximum shear stress and maximum torque with the different heat treatment temperatures at same soaking time

Cyclic data have been collected from the cantilever fatigue test for AA6063 sample having heat treated at 100℃ for 2 hour and provided in Table 4.6. Thirteen samples were tested, the strain – life relation is plotted for these samples and shown in Fig. 4.13. The plot illustrates elastic strain line, plastic strain line and total strain curve. The plot also shows transition fatigue life and two regions viz. elastic region and plastic region. In a similar way the low cycle fatigue data for other heat treatment cases i.e. 200℃ and 350℃ for 2 hour is shown in Table 4.7 and Table 4.8, respectively. Twelve and thirteen samples were tested for these two cases, respectively. The strain life relation for these two cases are also plotted in Fig. 4.14 and Fig. 4.15, respectively. Figure 4.16 elaborates total strain-life curves for as received AA6063, heat treated AA6063 at 100℃, 200℃ and 350℃ for 2 hour for low cycle fatigue test. The comparion shows that heat treated sample at 350℃ for 2 hour is having maximum transition fatigue life. The comparison of different fatigue parameters viz. $\varepsilon_f^{'}$, $\sigma_f^{'}/E$, b, c, n′, K′ and N_T are shown in Table 4.9 for different heat treatment cases at same soaking time and for as received case also.

Table 4.6 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 100℃ with soaking time of 2 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
54120	0.00186	0	0.00186
25350	0.00192	0	0.00192
18530	0.00197	0	0.00197
12896	0.00201	0	0.00201
10550	0.00205	0	0.00205
8433	0.00308	0.01486	0.01794
6198	0.00314	0.01941	0.02255
5300	0.00325	0.02806	0.03131
3208	0.0034	0.03439	0.03779
2400	0.00357	0.04804	0.05161
2736	0.00367	0.05856	0.06223
2650	0.00373	0.06623	0.06996
1811	0.00389	0.08914	0.09303

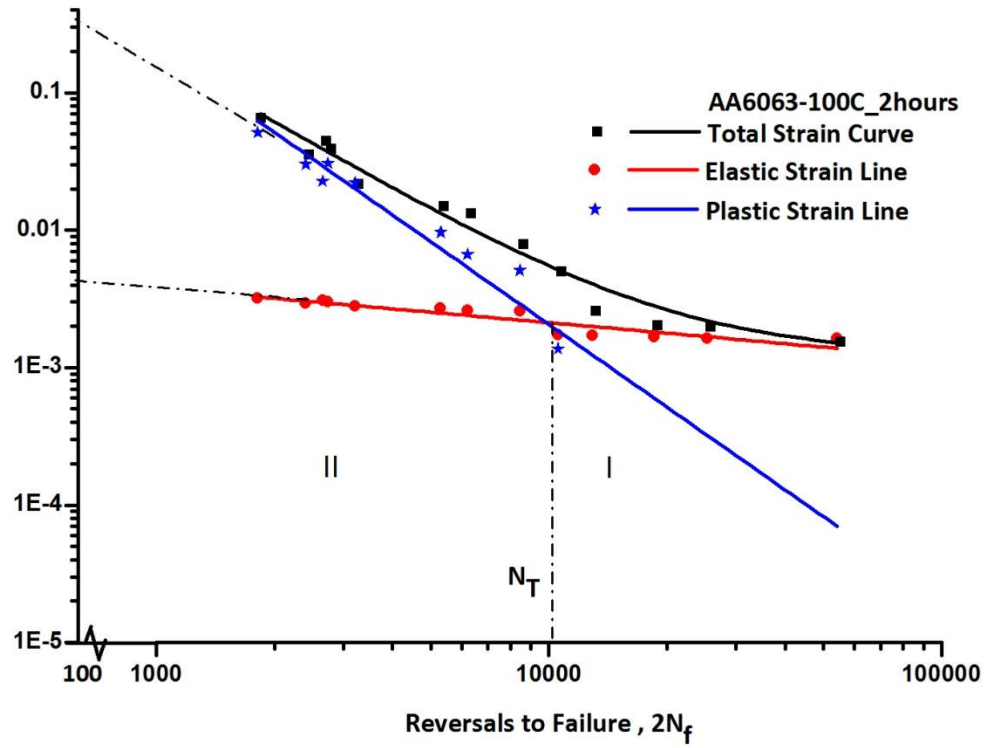

Fig. 4.13 Strain life curves for AA6063 alloy heat treated at 100℃ with soaking time of 2 hours

Table 4.7 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 200℃ with soaking time of 2 hours

Number of cycles to failure (N_f)	Elastic Strain Amplitude	Plastic Strain Amplitude	Total Strain Amplitude
60512	0.00222	0	0.00222
37309	0.00237	0	0.00237
17344	0.00261	0	0.00261
2214	0.00306	8.45E-4	0.0039
2335	0.00323	0.00159	0.00482
2460	0.0039	0.01584	0.01974
1865	0.00425	0.4338	0.43805
1565	0.00442	0.06884	0.07326

909	0.00459	0.10559	0.11018
926	0.00475	0.15896	0.16371
823	0.00492	0.23331	0.23823
792	0.00503	0.29244	0.29747

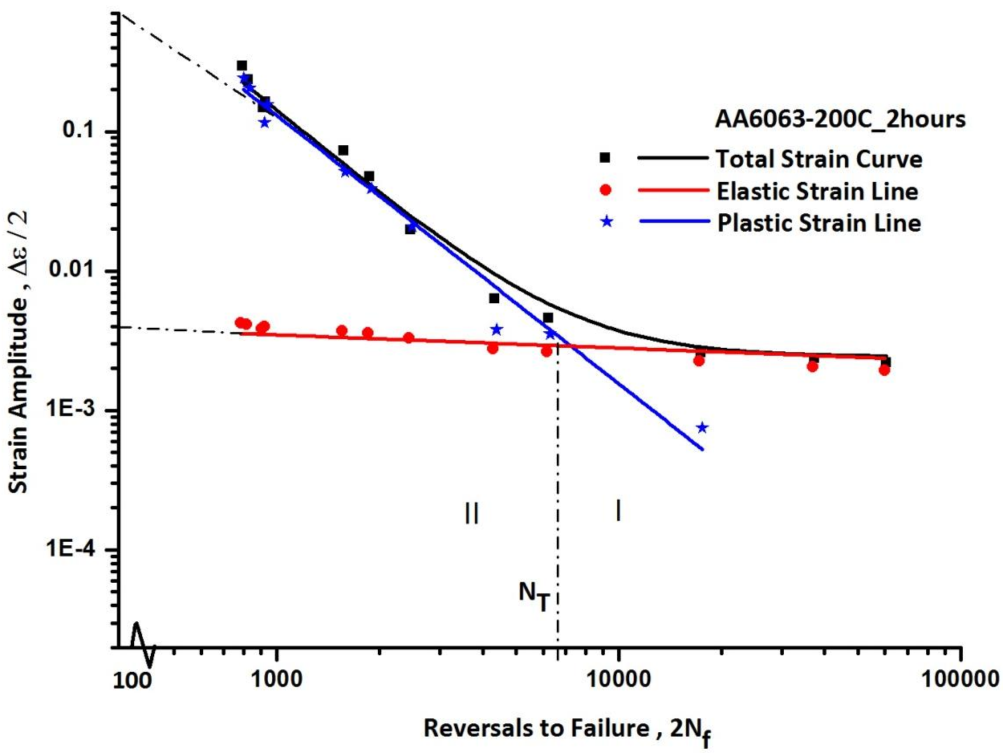

Fig. 4.14 Strain life curves for AA6063 alloy heat treated at 200℃ with soaking time of 2 hours

Table 4.8 Cyclic data for rotating cantilever low cycle fatigue test of AA6063 alloy heat treated at 350℃ 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

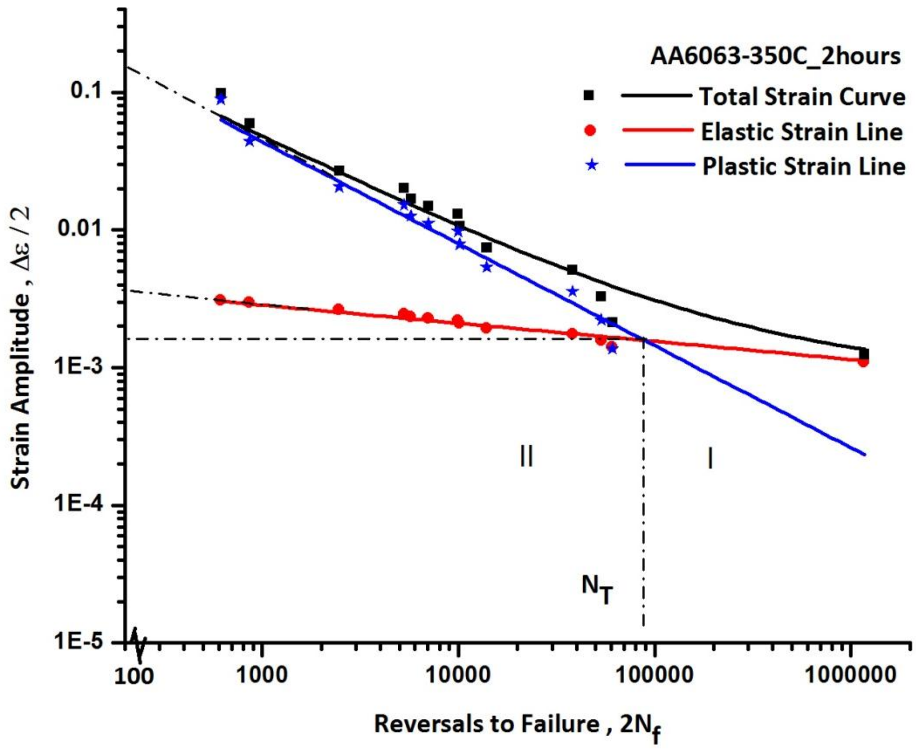

Fig. 4.15 Strain life curves for AA6063 alloy heat treated at 350℃ with soaking time of 2 hours

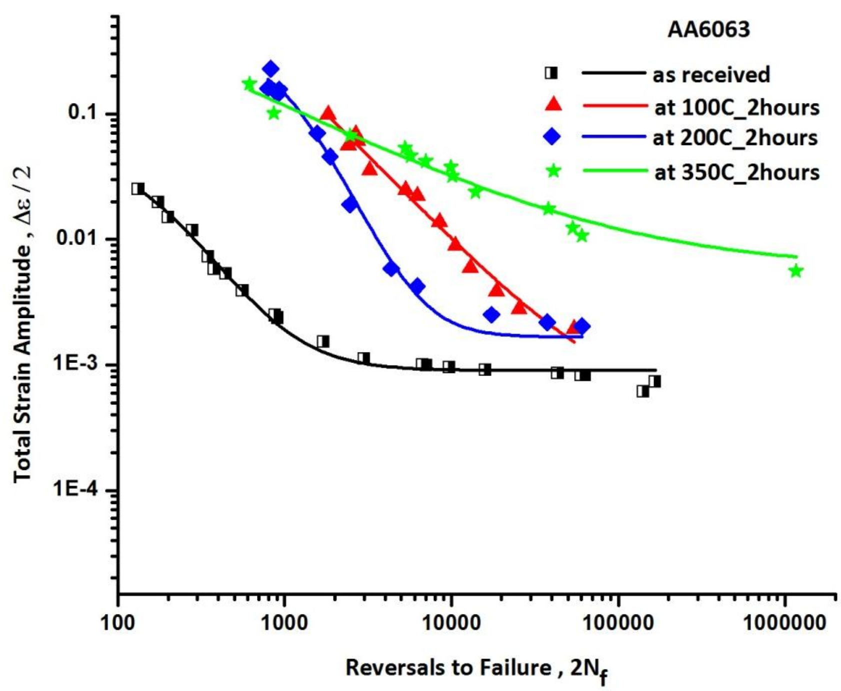

Fig. 4.16 Total strain-life curves for AA6063 at different heat treatment temperatures with same soaking time

Table 4.9 Low cycle fatigue properties of aluminum alloy AA6063 at different heat treatment temperatures with same soaking time

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
6063-100℃_2hr	0.2935	0.004882	317.33	-0.166	-1.3	0.1276	371.06	10294
6063-200℃_2hr	0.6018	0.00476	295.55	-0.15	-1.52	0.09868	310.73	6618
6063-350℃_2hr	0.148	0.00379	227.4	-0.13	-0.6	0.216	343.56	87568

Figure 4.17 shows variation of transition fatigue life with respect to heat treatment temperature. The variation of fatigue strength coefficient and fatigue ductility exponent with heat treatment temperature are illustrated in Fig. 4.18. Figure 4.19 demonstrates the variation of cyclic strain exponent and cyclic strength coefficient with respect to heat treatment temperature. Variation of cyclic plastic strain and fatigue strength coefficient with respect to heat treatment temperature is illustrated in Fig. 4.20.

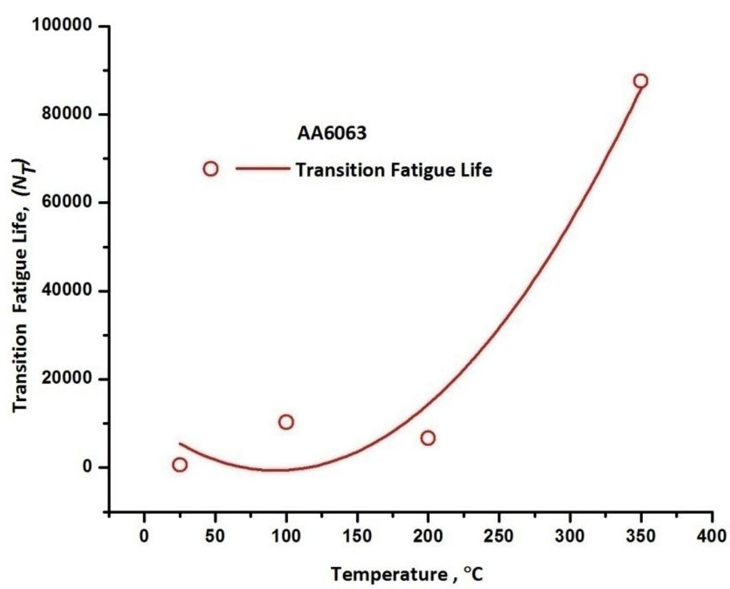

Fig. 4.17 Variation of transition fatigue life with different heat treatment temperature at same soaking time

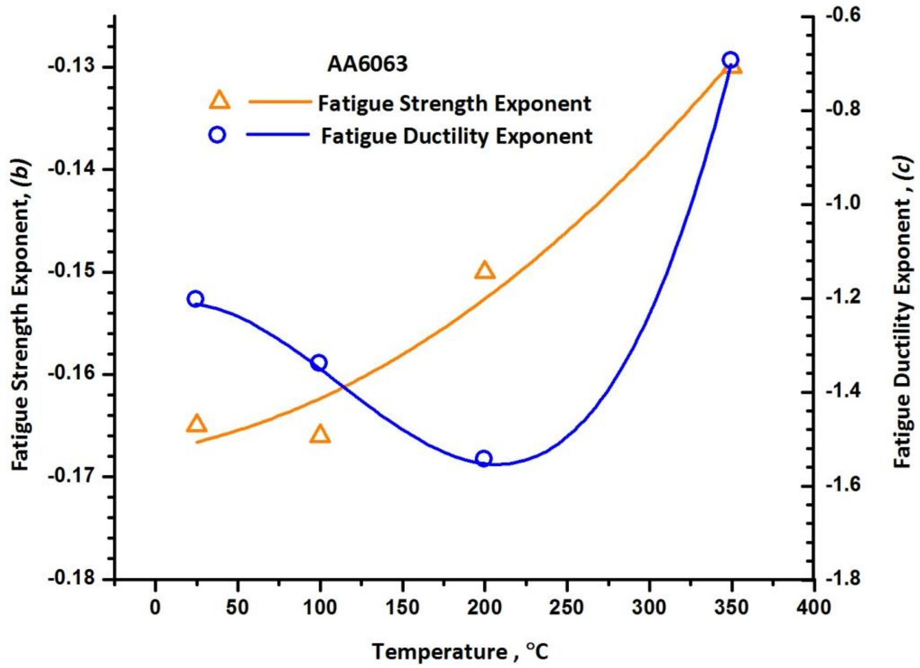

Fig. 4.18 Variations of fatigue Strength Exponent and Fatigue Ductility Exponent with different heat treatment temperature at same soaking time

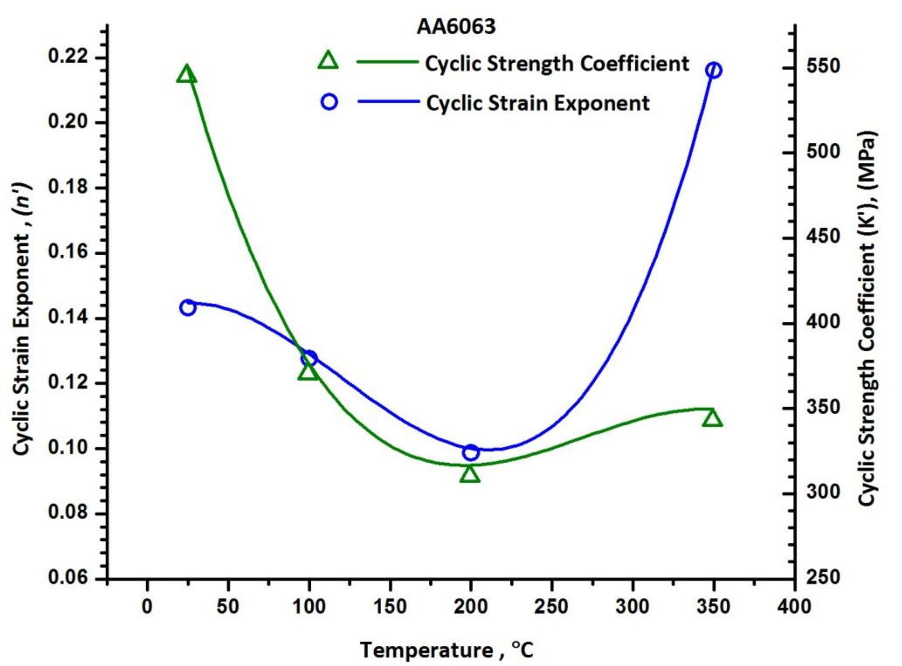

Fig. 4.19 Variations of cyclic Strain Hardening Exponent, n´ and strength coefficient K´ with different heat treatment temperature at same soaking time

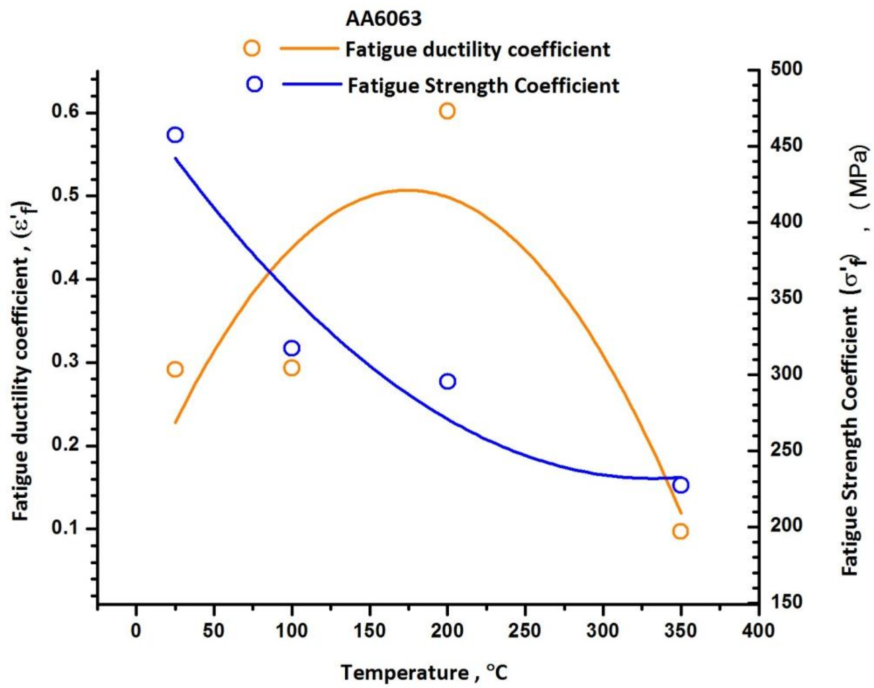

Fig. 4.20 Variations of fatigue Strength Coefficient (σ_f') and cyclic plastic strain (ε_f') with different heat treatment temperature at same soaking time

Table 4.10 and Table 4.11 shows the comparison of elastic and plastic strains, respectively, by experimental method with numerical method and two empirical methods viz. SWT and Morrow.

Table 4.10 Comparison of experimental, numerical and empirical results of elastic strain for AA6063 with different heat treatment temperature at same soaking time

Condition	Force (N)	Cycles	Elastic Strain						
			Exp.	FEM	% Diff.	SWT	% Diff.	Morrow	% Diff.
6063-100℃_2hr	120	1811	0.00389	0.0037236	4.27	0.000507	86.97	0.001405	63.873
6063-200℃_2hr	148	792	0.00503	0.0049117	2.35	0.00609	87.92	0.001752	65.177
6063-350℃_2hr	85	613	0.00299	0.002849	4.71	0.000812	72.838	0.00159	47.87

Table 4.11 Comparison of experimental, numerical and empirical results of Plastic strain for AA6063 with different heat treatment temperature at same soaking time

Condition	Force (N)	Cycles	Plastic Strain						
			Exp.	FEM	% Diff.	SWT	% Diff.	Morrow	% Diff.
6063-100℃_2hr	120	1811	0.08914	0.089151	0.01234	6.15E-6	99.93	1.71E-5	99.981
6063-200℃_2hr	148	792	0.29244	0.28737	1.73	8.21E-6	99.97	2.36E-5	99.992
6063-350℃_2hr	85	613	0.09838	0.10153	3.2	0.001069	98.93	0.002051	97.915

Figures 4.21, 4.22, 4.23 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 figures that plastic strain is constant over time while elastic strain varies between maximum value of 0.004 and minimum value of 0.00368748 for heat treatment temperature of 100℃ and soaking time of 2hours case, maximum value of 0.0211438 and minimum value of 0.0211428 for heat treatment temperature of 200℃ and soaking time of 2hours case and maximum value of 0.00284982 and minimum value of 0.00184485 for heat treatment temperature of 350℃ and 2hours of soaking time case.

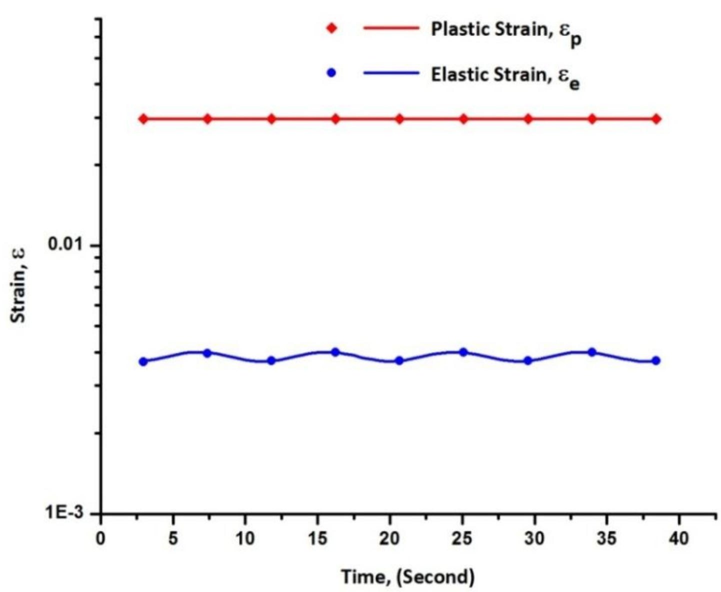

Fig. 4.21 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 100℃ with2hours of soaking time

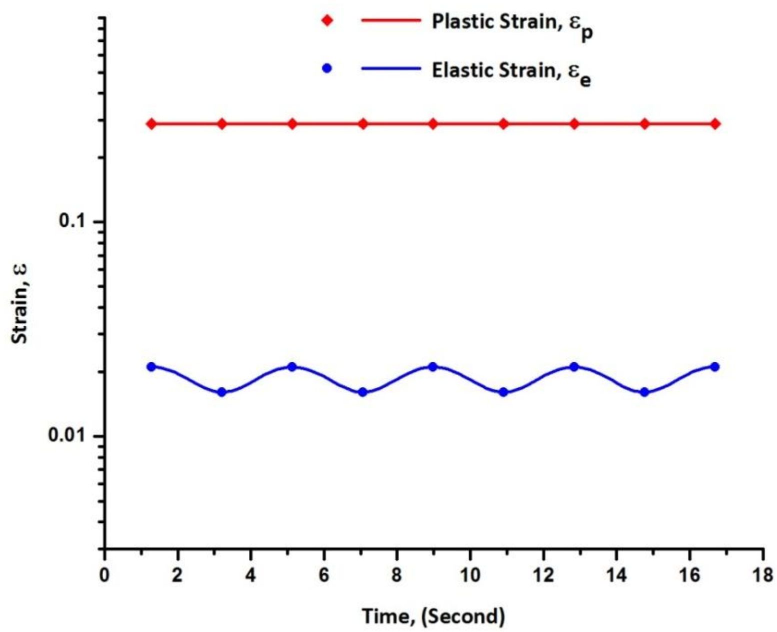

Fig. 4.22 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 200℃ with2hours of soaking time

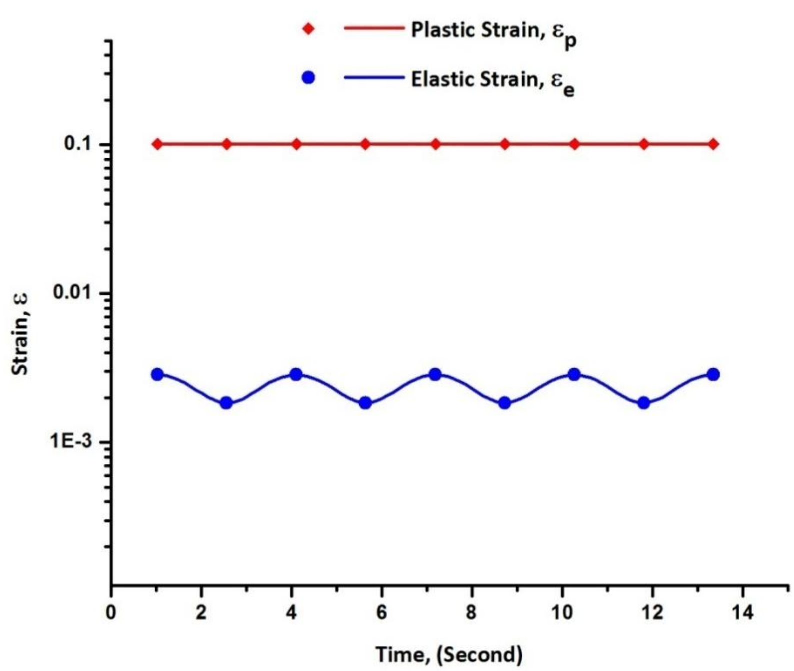

Fig. 4.23 Time history plot of elastic and plastic strain at surface node on cross section of fracture for AA6063 heat treated at 350℃ with2hours of soaking time

Figures 4.24 and 4.25 show deformed shape of the AA6063specimen heat treated at 100℃ with 2 hours of soaking time at a particular instant of time for elastic and plastic strain distributions, respectively. And Figs. 4.26 and 4.27 show deformed shape of the AA6063specimen heat treated at 200℃ with 2 hours of soaking time at a particular instant of time for elastic and plastic strain distributions, respectively. Also Figs. 4.28 and 4.29 show deformed shape of the AA6063specimen heat treated at 350℃ with 2 hours of soaking time at a particular instant of time for elastic and plastic strain distributions, respectively.

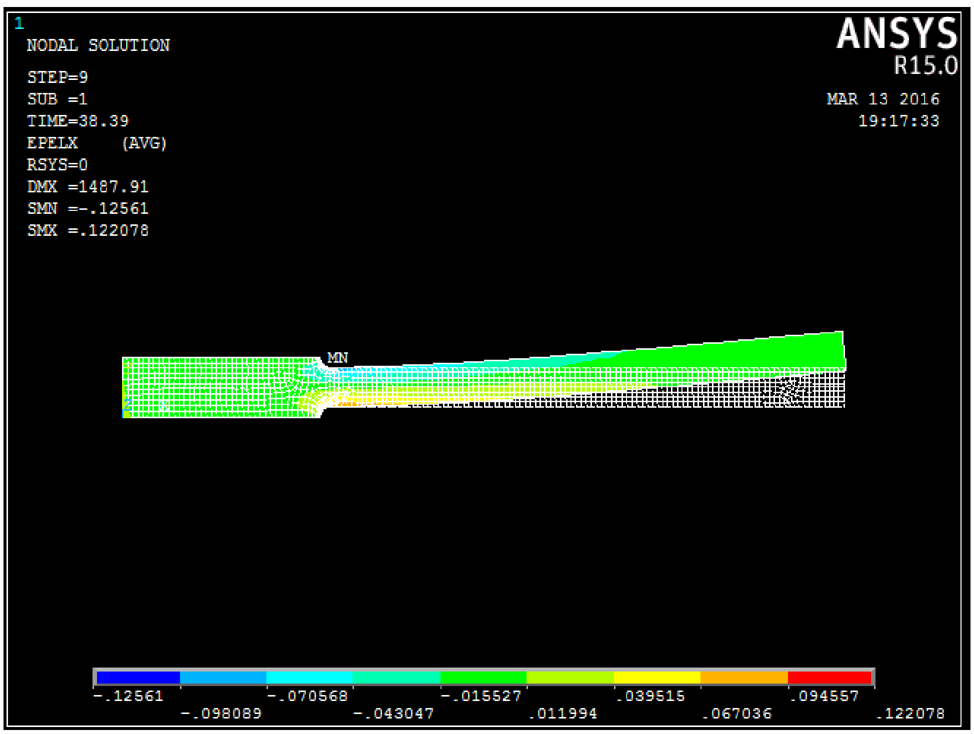

Fig. 4.24 Elastic strain at particular time on deformed shape for AA6063 heat treated at 100℃ with 2 hours soaking time

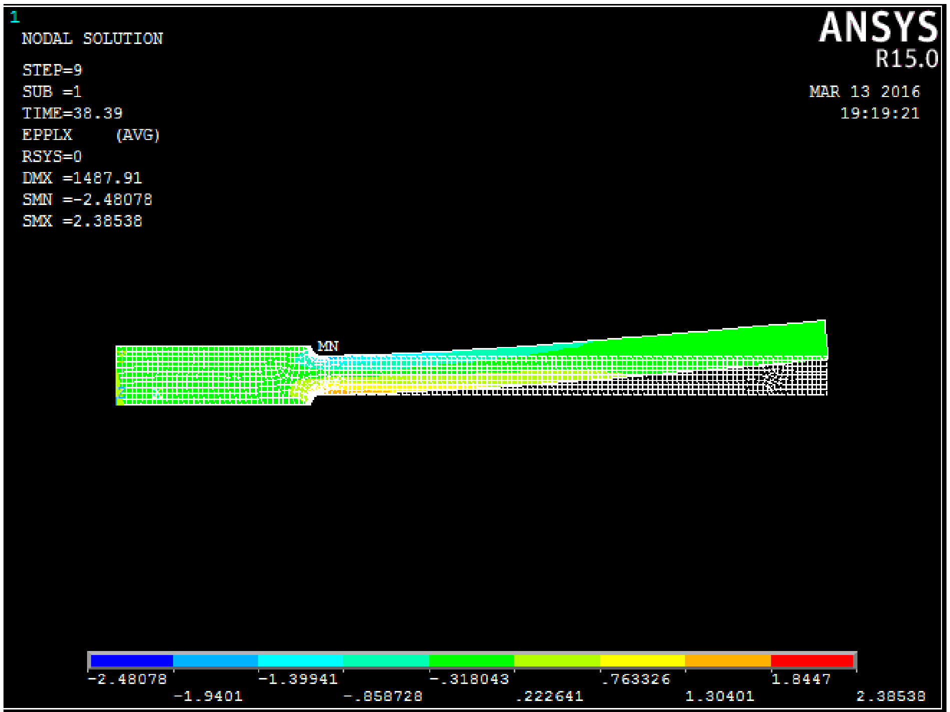

Fig. 4.25 Plastic strain at particular time on deformed shape for AA6063 heat treated at 100℃ with 2 hours soaking time

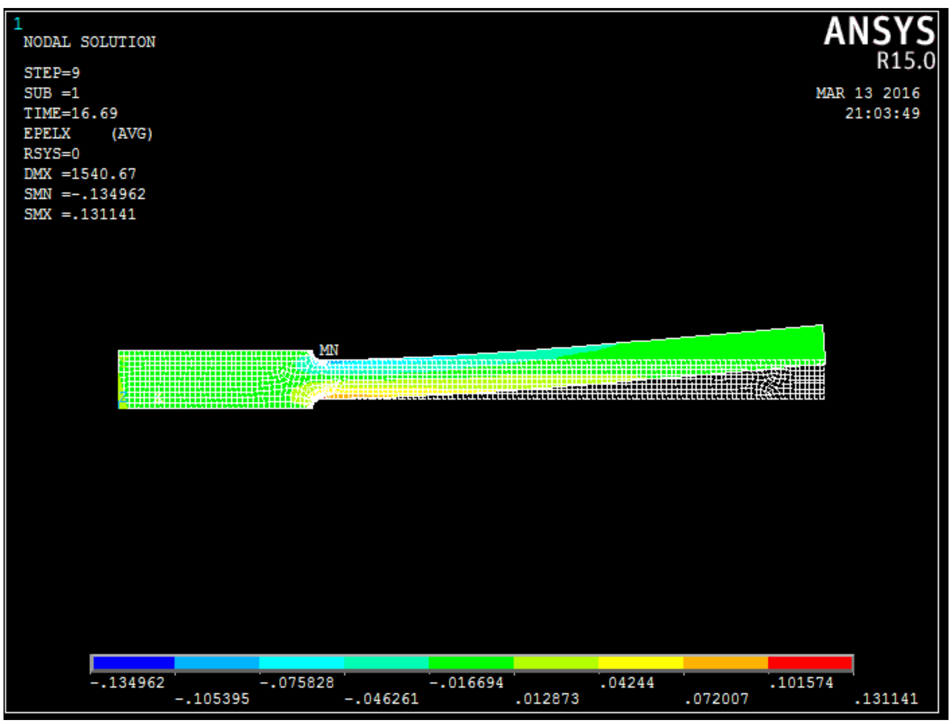

Fig. 4.26 Elastic strain at particular time on deformed shape for AA6063 heat treated at 200℃ with 2 hours soaking time

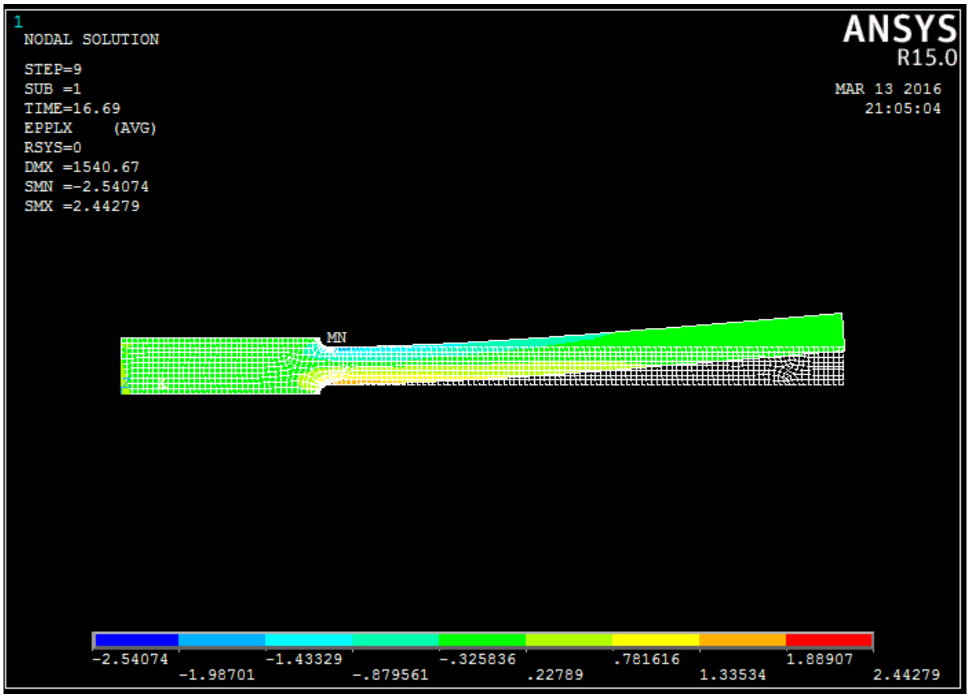

Fig. 4.27 Plastic strain at particular time on deformed shape for AA6063 heat treated at 200℃ with 2 hours soaking time

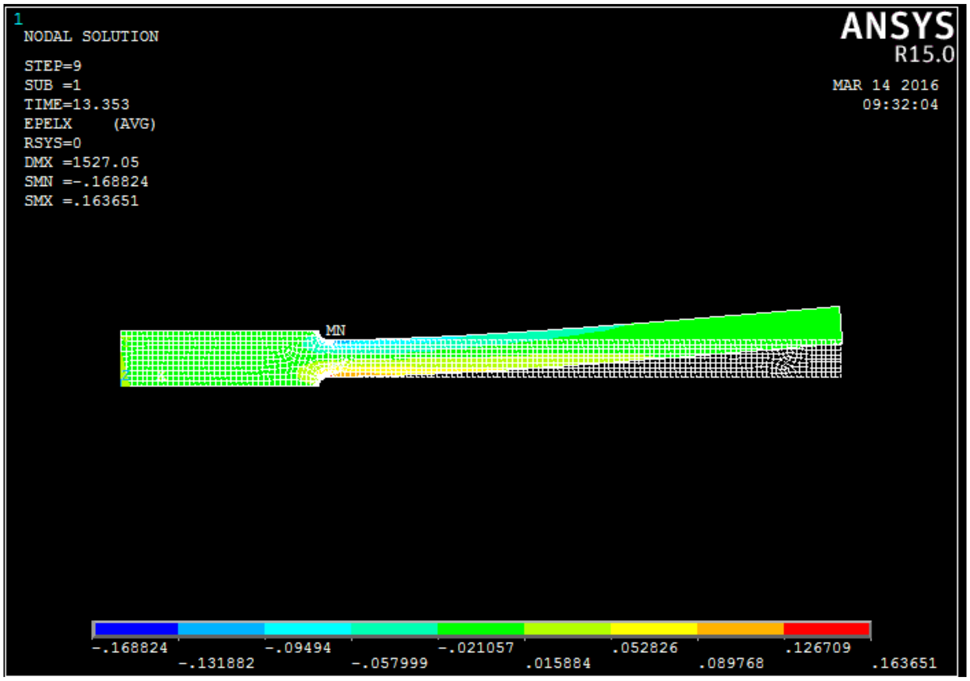

Fig. 4.28 Elastic strain at particular time on deformed shape for AA6063 heat treated at 350℃ with 2 hours soaking time

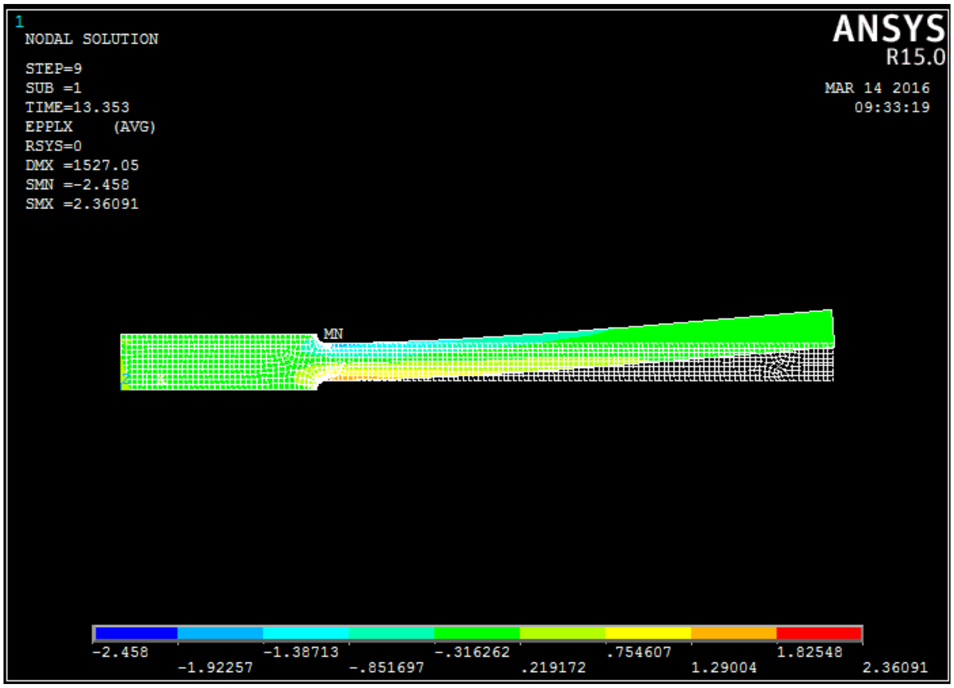

Fig. 4.29 Elastic strain at particular time on deformed shape for AA6063 heat treated at 350℃ with 2 hours soaking time

Figures 4.30, 4.33 and 4.36 demonstrate fitted lines for elastic strain-life data by experimental method, least square analysis, regression for model I and model II. Different lines show good fitting as points lie evenly above and below each line for heat treatment temperature of 100℃ with 2hours of soaking time, respectively. Similarly Figs. 4.31, 4.32, 4.34, 4.35,4.37 and 4.38 show fitting of plastic and total strain-life data by experimental, least square, regression model I and model II also, respectively.

Table 4.12 shows values of R^2 and modified R^2 for elastic , plastic and total strain data.

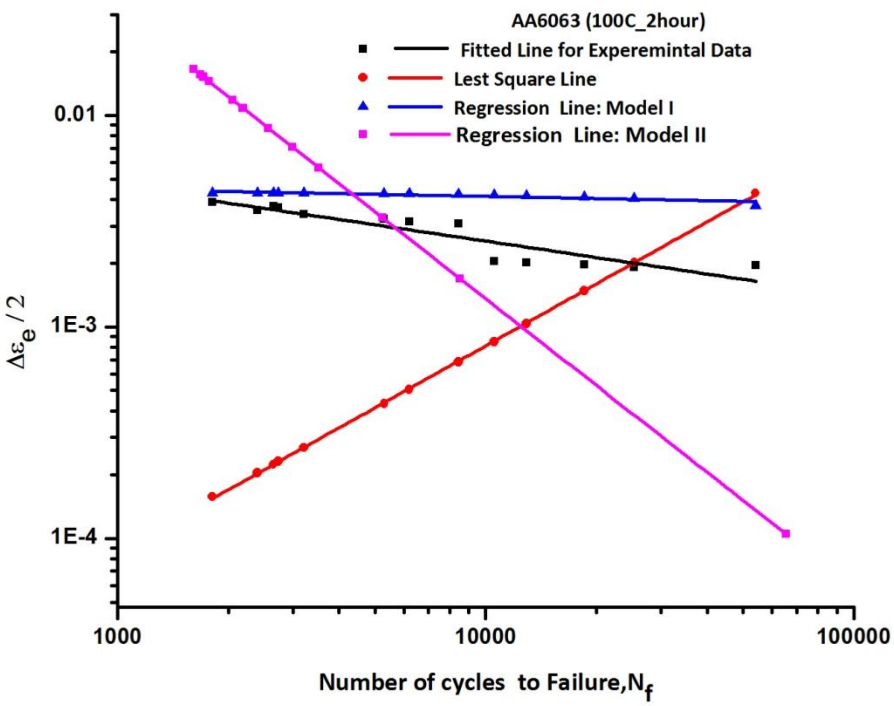

Fig. 4.30 Fitted elastic strain lines by empirical methods

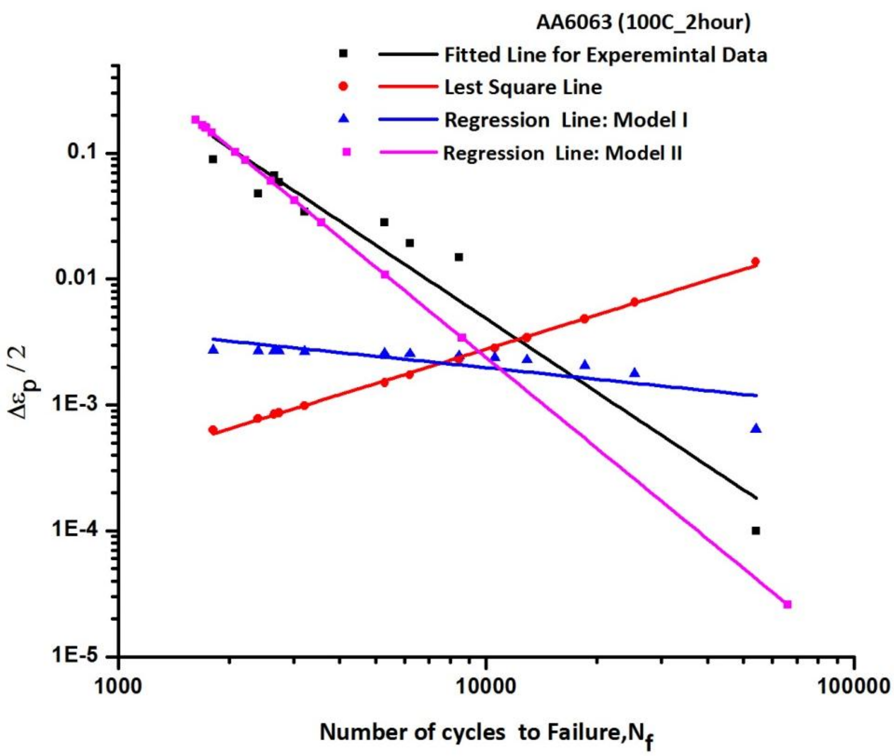

Fig. 4.31 Fitted plastic strain lines by empirical methods

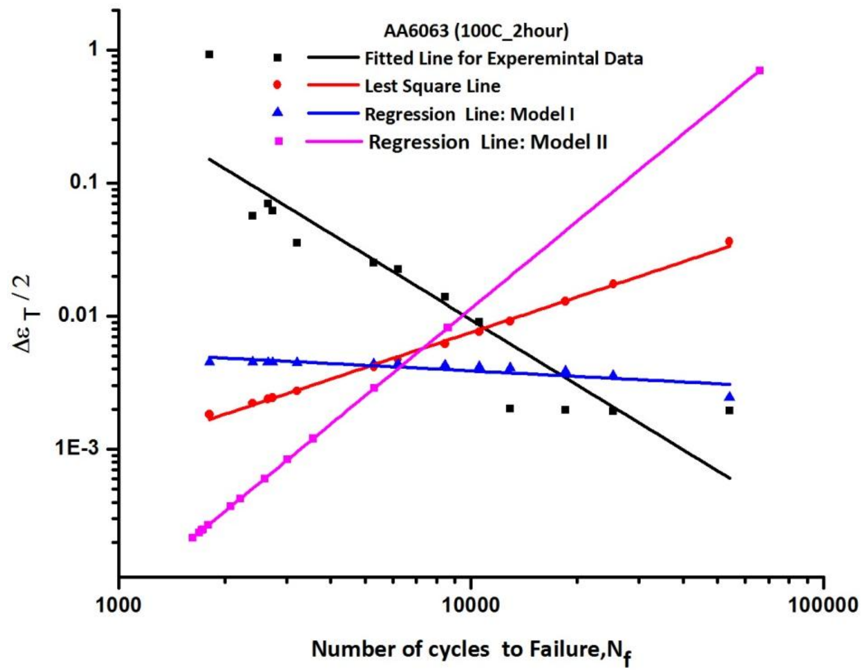

Fig. 432 Fitted total strain lines by empirical methods

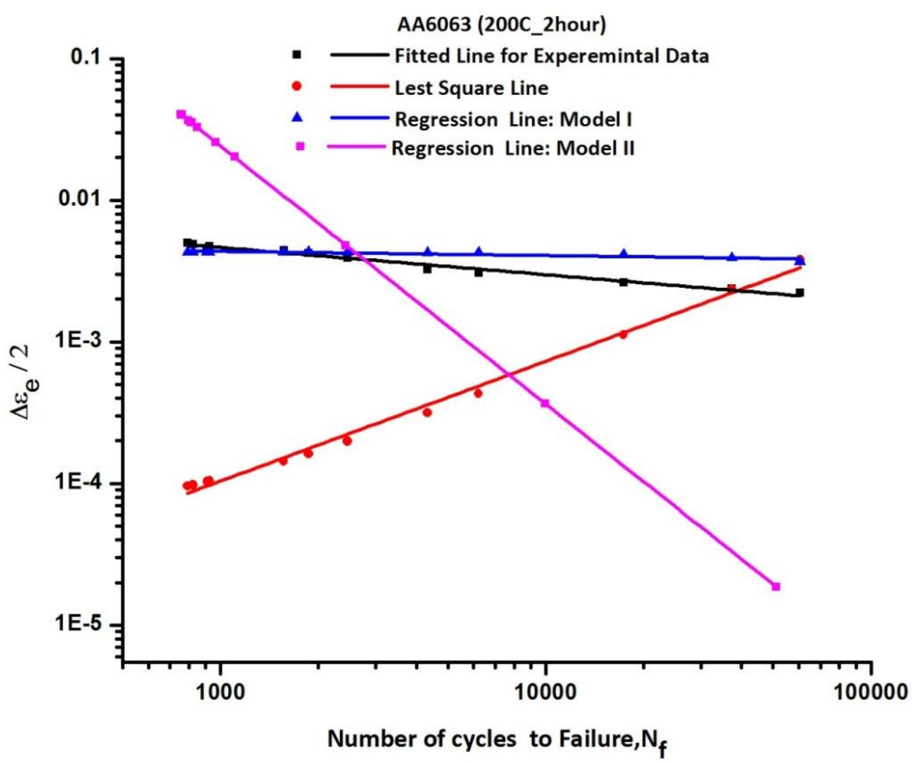

Fig. 4.33 Fitted elastic strain lines by empirical methods

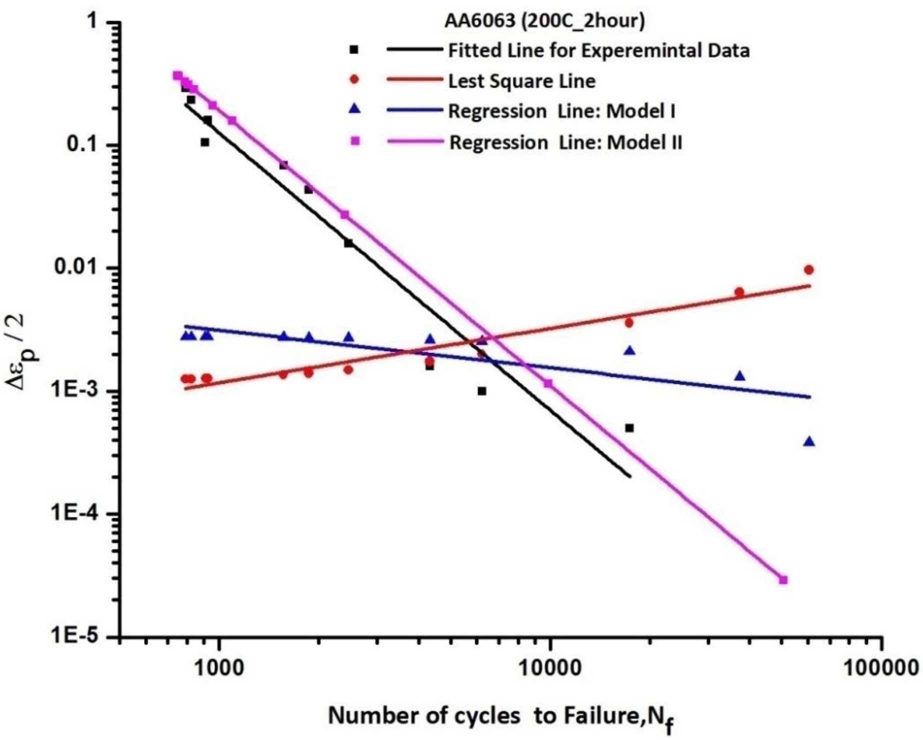

Fig. 4.34 Fitted plastic strain lines by empirical methods

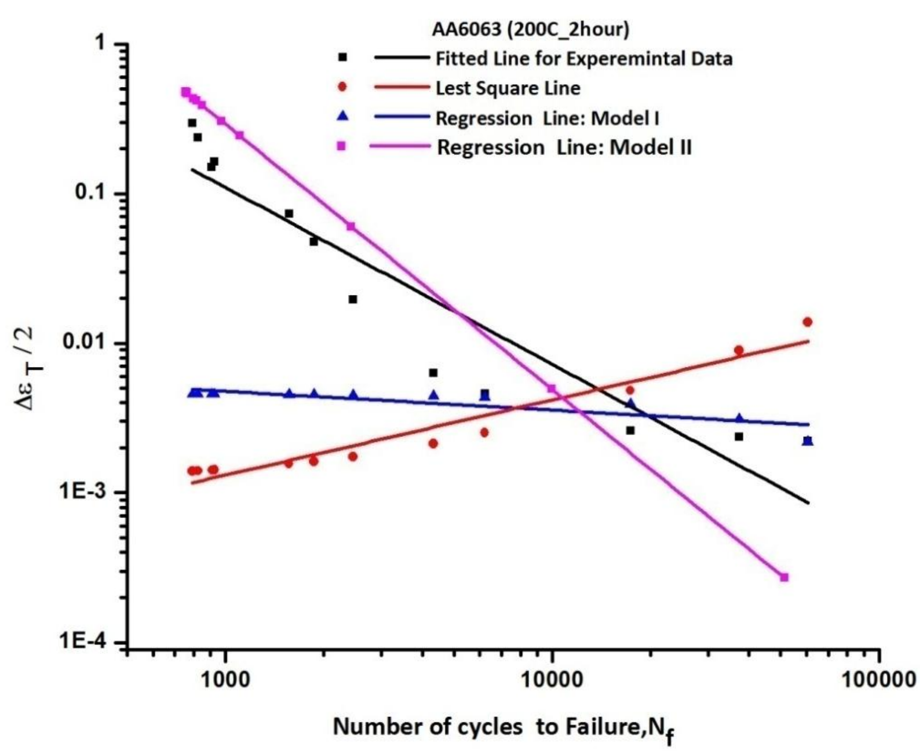

Fig. 4.35 Fitted total strain lines by empirical methods

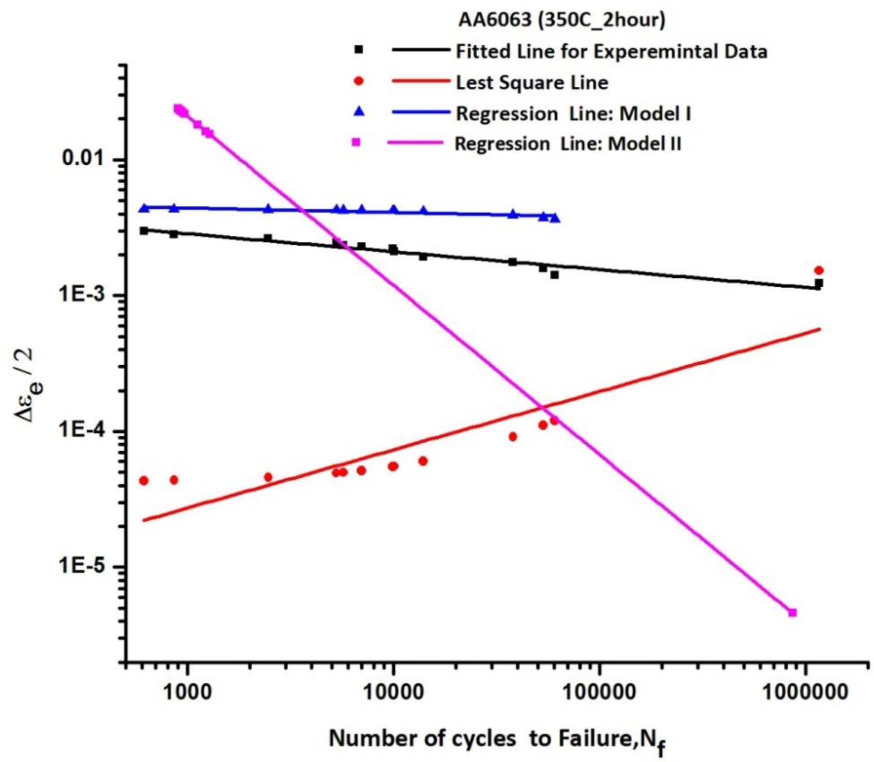

Fig. 4.36 Fitted elastic strain lines by empirical methods

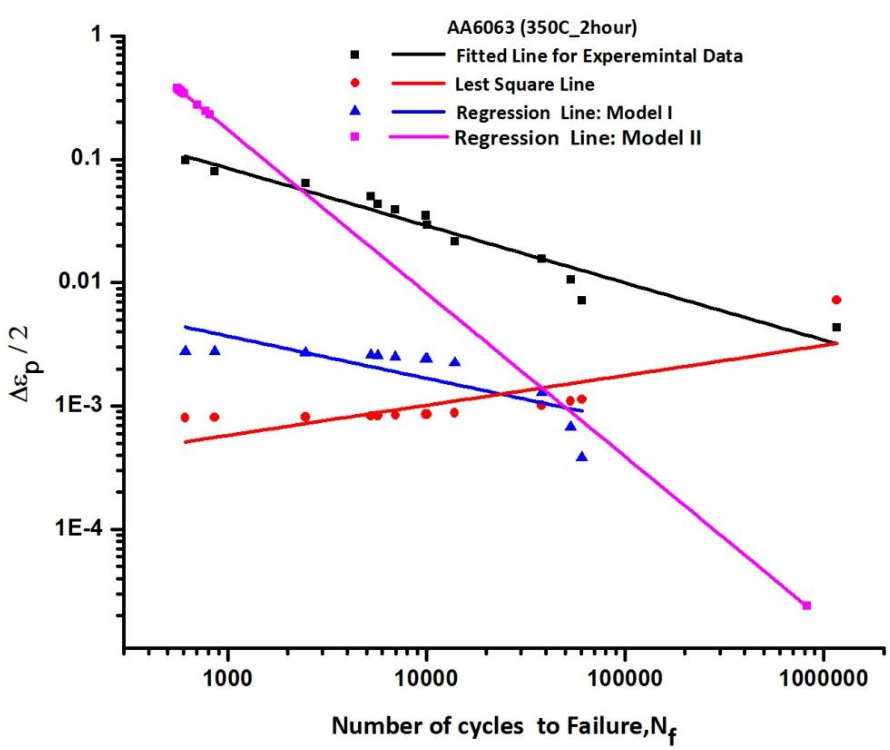

Fig. 4.37 Fitted plastic strain lines by empirical methods

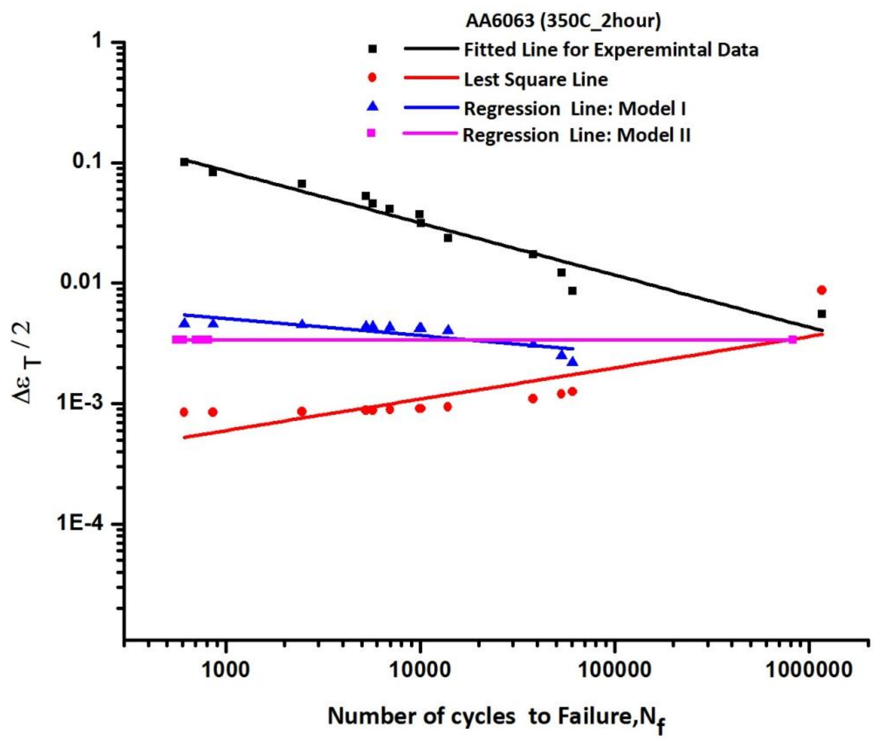

Fig. 4.38 Fitted total strain lines by empirical methods

Table 4.12` R^2 and modified R^2 values for elastic , plastic and total strain for AA6063 with different heat treatment temperature at same soaking time

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
AA6063-100℃_2hr	R^2	0.001688	1.3321	0.21843
	Mod. R^2	-9.0891	-7.6377	-8.8526
AA6063-200℃_2hr	R^2	11.46	0.058529	0.11635
	Mod. R^2	2.6055	-9.9356	-9.872
AA6063-350℃_2hr	R^2	3.5747	0.14449	0.20151
	Mod. R^2	-5.1912	-8.9333	-8.8711

Figures 4.39 to 4.41 explain how SWT parameter remain constant for AA6063 alloy heat treated at 100℃ , 200℃ and 350℃ and with same soaking time of 2 hours, respectively, for rotating bending LCF data.

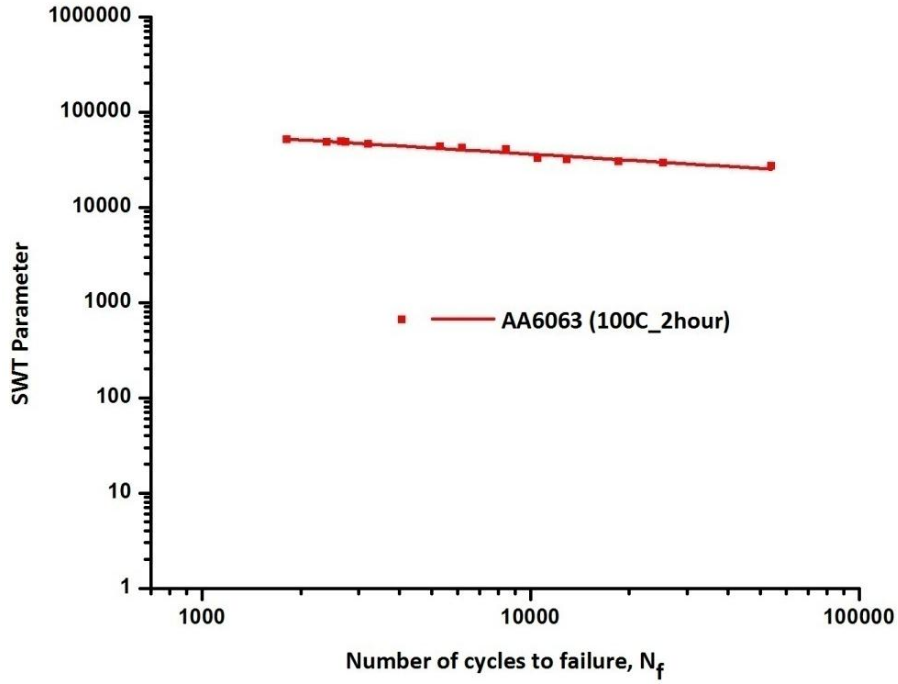

Fig. 4.39 Variation of SWT parameter with number of cycles to failure

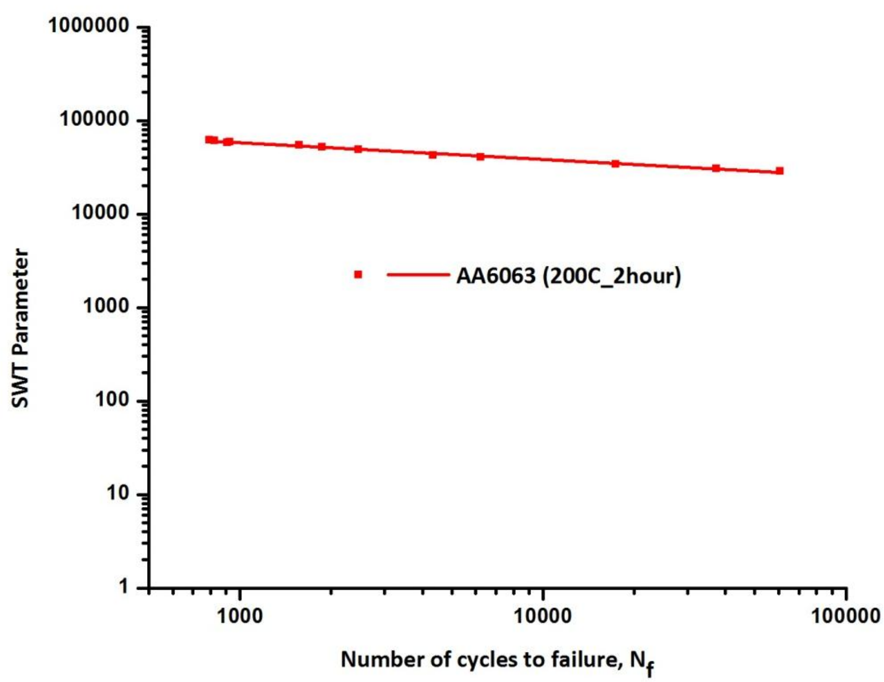

Fig. 4.40 Variation of SWT parameter with number of cycles to failure

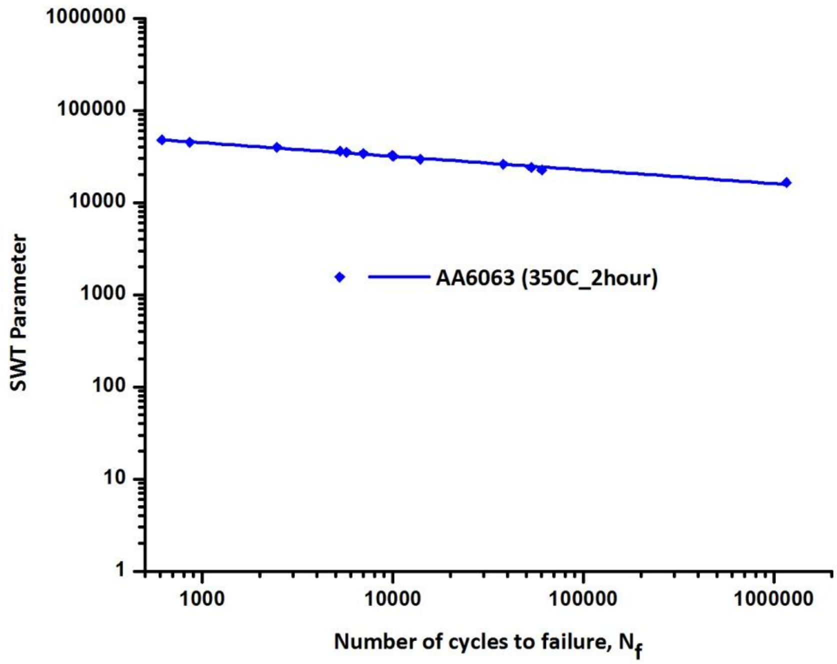

Fig. 4.41 Variation of SWT parameter with number of cycles to failure

4.3 Conclusion

This chapter investigated on the effect of heat treatment temperature on low cycle fatigue behavior of AA6063 aluminum alloy at constant soaking time of two hours. It is observed that as heat treatment temperature is increased to 350C, the transition fatigue life considerably increased to a higher value than un-treated as received AA6063 and low temperature treatments. The next chapter will address the effect of soaking time on low cycle fatigue behavior of AA6063 alloy.