Chapter 1

Introduction

1.1 Fatigue

Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue may culminate into cracks and cause fracture after a sufficient number of fluctuations. Fatigue damage is caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain. If any one of these three is not present, a fatigue crack will not initiate and propagate. The plastic strain resulting from cyclic stress initiates the crack; the tensile stress promotes crack growth (propagation). There are two approaches for fatigue analysis viz. cyclic strain testing and fracture mechanics. The strain control approach is aimed primarily at fatigue crack initiation and early fatigue crack growth, while fracture mechanics concepts address the propagation of an existing crack to failure. This combination of knowledge from cyclic strain testing and fracture mechanics provides a basis for understanding of fatigue processes beyond the historical emphasis on crack nucleation studies from stress-controlled (stress to number of cycles, or *S*-*N*) fatigue testing .

1.2 Low Cycle Fatigue

In low cycle fatigue the applied strain have a significant plastic component and resultant lives falls between 10 to 10^5, on the contrary, in high cycle fatigue the applied stress is primarily within elastic range of material and the resultant lives (cycles to failure-life) are high. The stress-life or S-N approach is standard for high cycle fatigue where as strain-life approach is suitable for low cycle fatigue analysis. Basquin [1] observed that for steel and copper materials the stress-life data could be linearized on log–log scale. High cycle fatigue has application in power transmission shafts and low cycle fatigue has applications in turbine blades. [2]

1.3 Aluminum Alloys

In the aluminum industry, significant progress has been achieved in providing "improved" alloys with good combinations of strength, fracture toughness, and resistance to stress-corrosion cracking. Optimum selection and use of fatigue-resistant of aluminum alloys has become more of a factor for designers and materials engineers for extending fatigue life and/or structural efficiency.

Commercial aluminum products used in the majority of structural applications are selected from 2xxx, 5xxx, 6xxx, and 7xxx alloy groups, which offer medium-to-high strengths. Of these, 5xxx and 6xxx alloys offer medium-to relatively high strength, good corrosion resistance, and are generally so tough that fracture toughness is rarely a design consideration. The 5*xxx* series (Al-Mg–based) and 6*xxx* series (Al-Mg-Si–based) alloys are used in automotive structural applications.

These multiphase alloys belong to the group of commercial aluminum alloys, in which relative volume; chemical composition and morphology of structural constituents exert significant influence on their useful properties.

The exceptional increase in strength obtained by precipitation hardening Al–Mg–Si (6xxx) alloys, the Al–Mg–Si alloys are mostly used in extruded aluminum products as well as for construction and automotive purposes. As an example of application, nowadays, aluminum–silicon–magnesium alloys have been widely used in diesel engine cylinder heads due to their relatively high strength to weight ratio, low cost, and providing affordable improvements in fuel efficiency. The ease with which these alloys can be shaped, their low density, their very good corrosion-and surface-properties and good weldability are factors that together with a low price make them commercially very attractive.

Table 1.1 shows different commercially available aluminum alloys, their major constituent elements, properties, applications, strengthening method and range of tensile strength [3].

Table 1.1 Different group of commercially available aluminum alloys

SL No.	Group	Major Alloying element	properties	Applications	Strengthening Method	Range of Tensile Strength (MPa)
1	1xxx		electrical conductivity, formability, ductility, and resistance to stress corrosion are more important than strength		cold working	70-175
2	2xxx	Cu Mg	good machining, electro plating and high strength at elevated temperature	highly stressed parts, good welding characteristics	heat treatment	170-310
3	3xxx	Si Cu	low strengths and very good toughness, ductility, formability, brazing, and welding characteristics	piping applications	cold working	140-280
4	4xxx	Si	Good welding, chemical oxide coating and electro plating characteristics	welding wire and brazing applications	cold working (some heat treatment)	105-350
5	5xxx	Mg Zn	good corrosion resistance, machining and polishing	Automatic structural applications	cold working	280-380

6	6xxx	Mg Si		Conventional structural applications	heat treatment	150-380
7	7xxx	Zn Mg	Good machining, polishing and anodizing	highly stressed parts and brazing	heat treatment	380-520
8	8xxx	Ti	Good welding characteristics and good corrosion resistance	highly stressed parts	heat treatment	280-560

1.4 Heat Treatment

Material should be quenched from the solution-treating temperature as rapidly as possible and with minimum delay after removal from the furnace. When material is quenched by total immersion in water, unless otherwise indicated, the water should be at room temperature, and should be suitably cooled so that it remains below 38 °C (100 °F) during the quenching cycle. Use of high-velocity, high-volume jets of cold water also is effective for some materials. Cold working after solution treatment is necessary to attain specified properties during precipitation heat treatments, Stress is relieved by 1 to 5% subsequent to solution heat treatment and prior to precipitation heat treatment [4] .

1.5 Metal Matrix Composite (MMC)

Metal matrix composites (MMC) are promising materials for lightweight, high strength structural applications. In particulate MMCs non-metallic particles are incorporated in metallic alloys to improve their elastic modulus and strength. However, introducing reinforcement particles with high modulus to the matrix alloy can reduce the fracture toughness and change the fatigue resistance of the material. The effects of reinforcement on cyclic fatigue damage and crack initiation, its role on constraining matrix plastic flow during cyclic deformation and the response of the material are important aspects in low cycle fatigue (LCF) of MMCs.

1.6 Strain – Controlled Method

The strain-based approach for fatigue problems is widely used at present, especially in the low-cycle fatigue (LCF) loading of machine parts and structures [5]. Strain can be mesauared and has been shown to be an excellent quantity for correlating with low cycle fatigue. For example gas turbines operate at fairly steady stresses, during starting or stopping, they are subjected to a very high stress range. The local stress can be well above the yield stress, and the stresses are more difficult to measure or estimate than the strains [6]. When the load levels are low, stresses and strains are linearly related, at high load levels in the low cycle fatigue (LCF) regime the cyclic stress-strain response and the material behavior are best modeled under strain-controlled conditions [2]. Strain-life fatigue curves, which are also often called low-cycle fatigue curves, are plotted on log–log scales and total strain amplitude is resolved into elastic and plastic strain components based on data from the steady-state hysteresis loops.

1.7 Microstructure analysis

Electron microscopes are used in the study of microstructure of fracture surface. The X-RD microanalysis can also be used to study phase composition of the surface layer of a fracture, and in particular inclusions or precipitates can be identified which are responsible for a given image of the fracture. Investigations on microstructure of fatigue fracture are concerned principally at out the real fatigue fracture area with all its specific features. Observation of the final rupture surface and the pulling off stage provides information about the character of the cracking in these zones and about whether the cracking had been plastic or brittle or mixed. Material said to be plastic does not always crack plastically, just as material said to be brittle need not display brittle fracture. Brittle fracture is taken to mean fracture without macroscopic plastic strain, the local plastic strain always exists ahead of the tip of a brittle crack propagating in metals. Plastic or ductile fracture is preceded by macroscopic plastic strain due to deformation in the slip planes as a result of higher fracture resistance in the cleavage planes and at grain boundaries.

Plastic fracture is also called fibrous fracture because of its appearance of shear fracture because of the crack propagation mechanism. Plastic or ductile fracture is characterized by arrangements of dimples which form a kind of honeycomb structure. Dimples as a rule arise from microvoids which exist in the material or, most often, from microvoids which come into being and grow during loading until they combine under plastic strain and plastic fracture. Hence the dimple size must depend on the type, shape, size, distribution, and number of inclusions and precipitates, on the grain size, and on the plastic properties of the material. The dimple size coincides with the distance between inclusions or precipitates of small size. A distinction is made between more uniform dimples in the case of uniaxial uniform tension and elongated dimples with parabolic out line (like a fish scale) caused by shear or eccentric non uniform tension (also by tear). The last two varieties of dimple are distinguished according to whether the directions of elongated dimples on adjacent surfaces of the fracture are in agreement or not.

Striations are the trace of a crack advancing in each cycle. They are perpendicular, or almost so, to the direction of crack propagation, although various exceptions have been noted. Striations may be continuous and regular, as in aluminum alloys, with the separation between them varying with the stress and the crack growth rate. They may also be discontinuous and irregular. Striations are extremely distinct on fractures of solution-hardened and naturally-aged aluminum alloy with completely reversed bending. The striations depend on the state of the material, the heat treatment, and the load conditions. Brittle Striations have been found in high-strength materials and under corrosive action. These striations are in principle in the same direction as the principal crack propagation direction but local changes are possible [7].

1.8 Literature Review

Table 1.2 shows works already done by different researchers on Low Cycle Fatigue (LCF) analysis of different aluminum alloys and with heat treatments. Literature on low cycle fatigue of metal matrix composites of aluminum based alloys is presented in Table 1.3. The literatures relating to micro-structural investigations, theoretical analysis, empirical analysis and numerical analysis are presented in Tables 1.4, 1.5, 1.6 and 1.7 respectively.

Table 1.2 Literature review summery of aluminum alloys and with different heat treatments

Sl No	Name and Reference No.	Alloy	Heat Tratment	Theo. Method	Exp. Method
1	Zyad Nawaf Haji, 2010, [8]	AA2024-T6 & AA7020-T6	same heat treatment (T6) for both alloys	--	analyze the influence of chemical composition and strength
2	Salerno et. al., 2007, [9]	AA7175-T1	T1	Used empirical relationships developed by SWT, Morrow and Walker	Studied mean strain effect on total number of cycles to fatigue failure
3	Minichmayr et. al., 2008, [10]	AA3360	--	complex damage rate model of Neu/Sehitoglu was evaluated	Many LCF- and TMF-tests, including experiments in argon atmosphere, were conducted to determine the parameters of the model

4	Parsad et. al., 2003, [12]	AA1420	--	Review paper	--
5	Azadi et. al., 2013, [13]	A356 and A357	carried out at 535C for 8 h and after quenching, aging is performed at 180C for 3 h	--	low cycle fatigue tests are accomplished at evaluated temperatures under various strain rates (by changing the loading frequency) and different strain ratios (minimum to maximum strain).
6	Mrowka-Nowotnik et. al., 2005, [14]	AA6005 and AA6082	solution heat treatment temperature from 510 to 580 ◦C and then natural ageing in the room temperature	--	Effect of extrusion processing on microstructure and mechanical properties
7	Salazar-Guapuriche, et. al., 2006, [15]	AA7010	The full treatment cycle was: natural ageing at room temperature for more than 120 hrs; artificial ageing at 120ºC for 10 hours followed by 173ºC for 8 hrs to attain T7651 condition; and over ageing at 173ºC for 100 hrs	--	correlate strength with hardness and electrical conductivity so that the strength of the alloy can be determined nondestructively
8	Marioara, et. al., 2003, [16]	AA6082	Solution heat treatment 525C	--	effects of solution heat treatment (SHT) time on the mechanical properties for a range of deformation rates
9	Ortiz, et. al., 2007, [17]	AA6061, AA2024, AA7075	AA2024-T3,T8, O, T62 AA6061-T6, O AA7075-O, T62	--	The effects of the plastic strain on tensile properties, conductivity, hardness, and grain size are discussed and strain limits are suggested
10	Abdulwahab ,2008, [18]	7xxx series	Heat treatment: 490C-6hr Quenching: warm water Aging: 200C-6hr Cooling: air cooling	--	Studied effect of Mn content on tensile properties, hardness and impact energy
11	Siddiqui, et. al., 2008, [19]	AA6063	aged between 7 and 9 h and heat treated at temperatures between 160C and 200C, soaking time of 2 and 30 weeks	---	the effect of seawater corrosion, aging time, and aging temperature on the fatigue resistance property of 6063 aluminum alloy
12	Al-Marahleh, 2006, [20]	AA6063	Heat treated at 580°C for 10 h (4 h of heating and 6 h of holding), next cooled by air final aging at 200°C for 8 h	--	The effect of homogenizing on the properties of the alloy after extrusion is analyzed
13	Han,et.al., 2002, [21]	AA6063 and A356	Solution treated at 813 K for 8 h and water quenched, after holding at room temperature for 24 h, they were aged at 433 K for various hours	---	Stress_/strain response under cyclic loading at fixed plastic strain amplitude condition was examined, special attention was paid to the effect of solidification structure and aging condition on cyclic hardening behavior

14	Siddiqui, 2000, [22]	AA6063	under-aged, peak-aged and over-aged temperatures	--	The effect of precipitation on the tensile strength, yield strength, hardness, ductility and number of cycles required to fail the alloy at constant stress was investigated
15	Gupta, 2001, [23]	0.4%Mg, 1.3%Si, 0.25%Fe	--	--	the precipitation and hardening potential of different metastable precursors with help of DSC, TEM, hardness measurements
16	Gavgali, et. al., 2003, [24]	AA6063	aging treatments		The wear tests using on a pin-on-disc machine, characterization using hardness, profilometer, SEM, optical microscopy, XRD, EDS
17	Karamis, et. al., 2007, [25]	AA6063	These specimens were homogenized at 560 °C for 6 h and cooled down at five different rates, and annealed at 450 °C, 500 °C, and 550 °C for 1 h		effect of cooling rate during homogenization treatment on the low-grade cold deformation–recrystallization properties has been investigated using metallographic examination
18	Srivatsan, 2002, [26]	AA7055	T7751	--	the cyclic stress- and strain-amplitude-control fatigue response is presented
19	Borrego, et. al., 2004,[27]	AA6082-T6 AA6060-T6	T6	---	The low-cycle fatigue results are used for the characterisation of the cyclic plastic response and the fatigue live of the alloys

Table 1.3 Literature review summery of metal matrix composites of aluminum alloys

Sl No	Name and Reference No.	MMC	Heat Tratment	Theo. Method	Exp. Method
1	Koh, et. al., 1999, [28]	Al- Si (10wt%) +SiCp (10% and 20% by volume)	Heat treatment : T4 530°C for 5 hours quenching : in warm water of 40°C natural aging : at room temperature of 20°C.	--	The low-cycle fatigue has been investigated under strain-controlled conditions with and without tensile mean strains
2	Hall, et. al., 1994, [29]	AA2124 +SiCp	--	--	Strain-control LCF
3	Ding, et. al., 2002, [30]	AA6061 +Al_2O_3 (15 and 20 vol.%)	T6	Fracture mechanics approach : J integral and crack tip opening displacement (CTOD)	total-strain controlled symmetrical push–pull fatigue tests

4	Chawla, et. al., 1998, [31]	AA2080 +SiC (10%, 20% and 30 %)	T8 Solution treatment : 493 5 2 7C for 2 hours Quench: water cold rolling : 5 pct reduction in thickness, aging: 175 7C for 24 hours (peak aged).	--	Axial fatigue tests were carried out in stress control mode using a triangular waveform, *R* ratio (smin/smax) of 21, and a frequency of 30 Hz
5	Hadianfard, et. al., 2006, [32]	AA6061(D20)+ Al_2O_3 (20 vol%) And AA6061(C85)+ Al_2O_3 (20 vol%)	peak-aged (T6): solution heat treated : at 530 C for 1.5 h, quenched : cold water natural aged: at room temperature for 24h artificial ageing: at 175C for 8h.	--	strain-controlled fatigue testing
6	Shang, et. al., 1989, [33]	AA7091 +SIC(15-20% Vf and 5 µm)	--	Simple model developed to predict the magnitude of crack tip shielding during fatigue crack growth	--
7	Muratoglu, et. al., 2006, [34]	AA2124 +25 vol.% SiCp and 2.5, 15 µm	homogenization and age hardening on bonding properties		indicate that the application of aging before and after diffusion bonding decreases SiC particulate accumulation, and increases other elemental concentration at interface.
8	Uygur, et. al., 2002, [35]	AA2124 +SiCp (17 and 25vol%) and (2.5 and 15 µm)	T4 Solution treatment: at 505 C for 1 hour, Quenching: cold water. naturally aged: at room temperature for 100hours		Three different strain ratios (R= -1, fully reversed, R=0.5 and R=0 zero tension) were used with a triangular waveform of loading and a strain rate of 10^{-3} $s^{-1.}$
9	Li, W., et al., 2010, [36]	7Si–0.3Mg–0.01Mn–0.01Cu (mass%) +SiCp 15 vol.% (4.5 µm)	T6 in 535 ◦C for 2.5 h quenching : in cold water of 25 ◦C natural aging : at 160 ◦C for 7 h		A sinusoidal waveform was applied. The total-strain amplitude ($\Delta\varepsilon_t/2$) range was from 0.3% to 0.5%. The tests were carried out at constant cyclic frequency of 0.03 Hz and the load ratio was R =−1

Table 1.4 Literature review summery of micro-structural investigation

Sl No	Name and Reference No.	Alloy	Heat Tratment	Theo. Method	Exp. Method
1	Alan et al, 2003, [37]	AA5754 and AA6063	T7 overaged (5 hours at 218 °C)	--	All fatigue testing was conducted at room temperature in accordance with ASTM standard E466-96. Tension-tension loading with a minimum to

					maximum stress ratio (R) of 0.1 and a sinusoidal wave form was employed. The specimens were tested at frequencies between 30 and 70 Hz
2	Sha, et al, 2001, [38]	AA6xxx	--		SEM, TEM, XRD and DSC observation has been done
3	Tan, 2001, [39]	AA6066	Solutionized: 95 min and for 12 h at 4 different temperatures (515, 530, 540 and 550 ◦C)		SEM micro structural analysis

Table 1.5 Literature review summery of theoretical analysis of LCF

Sl No	**Name and Reference No.**	**Alloy**	**Heat Tratment**	**Theo. Method**	**Exp. Method**
1	Fatemi, et al, 2005, [40]	14 alloys 2xxx, 5xxx, 6xxx, 7xxx	T3 T6 T761 T651 T7351	Bi-linear S–N model	LCF
2	Eleiche, et al, 2006, [41]	26NiCr MoV115 (high strength medium alloy steel)	stress relief consisted of a preheating phase at 450 8C for 30 min heating phase: at 720 8C for 30 min, preheating: at 450 8C for 30 min and 720 8C for 15 min Heating: at 870 8C for 15 min Quenching: at 180 8C for 30 min. Tempering: salt bath for 30 min at 450, 580, 640 and 660 8C	Crack initiation method and Manson approach	LCF
3	Manson, et al, 2006, [42]	--	--	Hysteresis under cyclic plasticity	--
4	Megahed, et al, 1996, [43]	SAE 950X-150HB	--	LCF of rotating cantilever beam	--

Table 1.6 Literature review summery of empirical analysis of LCF

Sl No	**Name and Reference No.**	**Alloy**	**Heat Tratment**	**Theo. Method**	**Exp. Method**
1	Eleiche, et al, 2006, [41]	26NiCr MoV115 (high strength	stress relief consisted of a preheating phase at 450 8C for 30 min heating phase: at 720 8C	Crack initiation method and Manson approach	LCF

		medium alloy steel)	for 30 min, preheating: at 450 8C for 30 min and 720 8C for 15 min Heating: at 870 8C for 15 min Quenching: at 180 8C for 30 min. Tempering: salt bath for 30 min at 450, 580, 640 and 660 8C		
2	Chiou, et al, 2006, [46]	AISI 304 stainless steel	heat treated at atemperature of 480°C for ten minutes and then cooled in air	Watson Damage parameter	LCF
3	Walker, 1970, [48]	AA2024 and AA7075	T3 T6	SWT parameters	LCF
4	Megahed, et al, 1996, [43]	SAE 950X-150HB			

Table 1.7 Literature review summery of numerical analysis of LCF

Sl No	Name and Reference No.	Alloy	Heat Tratment	Theo. Method	Exp. Method
1	Barkanov, 2001, [49]	--	--	Basic of FEM	--
2	Szusta, et al, 2011, [50]	AA2007		Fatigue damage accumulation model for milt axial, non proportional low cycle loading using constitutive relations and kinematic hardening	LCF
3	Saraev, et al, 2003, [51]	Al/SiCp	--	Finite element calculations using axi-symmetric formulation	--
4	Aghdam, et al, 2000, [49]	--	--	Finite element micromechanical model for bi-axial and shear loading and compare with analytical model	--

5	Moraleda, et al, 2009, [50]	--	--	In plan finite deformation using computational micromechanics	
6	Boselli, et al, 2001, [52]	AA2124 + SiCp (18.7 vol.%)	--	Clustering of short crack growth behavior using micromechanical analysis	--

1.8.1 Low cycle fatigue of Aluminum Alloys

Haji [8] studied low cycle fatigue behavior of alloys AA2024-T6 & AA7020-T6 and showed that the precipitation of element zinc (Zn) with its parent metal in alloy AA7020-T6 is better than copper (Cu) in alloy AA2024-T6 under same heat treatment. They reported transition fatigue life experimentally to be about 780 and 20100 cycles for alloys AA7020-T6 and AA2024T6 respectively. They also reported that ductility and strength properties are significantly affected by the chemical composition and the strength of the alloy as both alloys are given same heat treatment. Salerno et al. [9] applied classical criteria for the LCF lifetime estimation of AA7175-T1 aluminum alloy to consider the mean strain effect.Minichmayr et al. [10] carried out TMF/LCF lifetime assessment of aluminum alloys using the damage rate model of Sehitoglu. [11] .

Prasad et al. [12] have taken aluminium–lithium alloys and studied the structure and mechanical properties with a view to indicate the directions that have been and can be pursued to overcome property limitations. According to the literature review, several papers focus on the strain ratio effect. But the strain rate and mean strain effects have been taken into account in fewer papers, like Azadi[13].

Mrowka-Nowotnik, et. al [14] studied the cooling conditions after homogenization of the AA6082 aluminium alloys and the effect of the solution heat treatment temperature on the mechanism and ageing kinetics of the two commercial wrought aluminum alloys AA6005 and AA6082. The alloys were heat treated with a wide range of solution heat treatment temperature ranging from 510 ℃ to 580 ℃ and then natural ageing at room temperature, and determined how extrusion processing affected the microstructure and mechanical properties of both aluminium alloys. Salazar-Guapuriche et. al. [15] investigated AA7010 under different temper and ageing conditions for tensile strength, proof strength, hardness and electrical conductivity with the aim to correlate strength with hardness and electrical conductivity. The relationship between strength and hardness was found to be reasonably linear, whereas the relationship between hardness and strength with electrical conductivity was non-linear. Marioara et. al. [16] designed and carried out a series of thermal-mechanical tests on the aluminium alloy AA6082 to investigate the effects of solution heat treatment (SHT) time on the mechanical properties for a range of deformation rates at the SHT temperature of 525 ℃. The experimental work has been carried out for different deformation and SHT conditions to validate the model predictions. The experiments verified that an increase in ductility and a decrease in maximum flow stress can be achieved by increasing the SHT time.

Ortiz et. al. [17] presented the study on AA6061, AA2024, and AA7075 under heat treatment to various tempers and subjected to a range of plastic strain (stretching) in order to determine their strain limits. Tensile properties, conductivity, hardness, and grain size measurements were also evaluated. The effects of the plastic strain on these properties are discussed and strain limits are suggested.

The mechanical properties upon age-hardening treatment to Al-Si-Fe-Mn alloy has been studied by Abduwahab[18].The produced alloys consist of varying manganese content from 0.1to 0.5 percent with constant Si-Fe composition and Al as the dominant constituent. As-cast alloys were produced and also age-hardened, the addition of Mn to the alloy increased the tensile properties and hardness subject to maximum 0.4 percent, for both the as-cast and age-hardened conditions. While the impact energies upon addition of Mn decreased with the age-hardened samples having better mechanical properties than the as-cast one. The effect of seawater corrosion, aging time, and aging temperature on the fatigue resistance property of AA6063 aluminum alloy was studied by Siddiqui et. al. [19]. The maximum fatigue resistance property in the AA6063 aluminum alloy was observed when aged between 7hour and 9hour and heat treated at temperatures between 160 ℃ and 200℃, and at constant load, the number of cycles to fail the AA6063 aluminum alloy decreased with increasing the soaking time in seawater. The results showed that the brittle fracture pattern tended to occur with the increase in aging time and temperature. The fatigue striations were observed very clearly at low and peak aging temperature.

The structure and properties of aluminum alloy AA6063 after extrusion in cast and homogenized states are studied by Al-Marahleh[20] . The volume fraction and the distribution of the second Mg_2Si phase are determined after different kinds of treatment. The structure and mechanical properties of shapes obtained from cast and homogenized billets are compared after aging and without aging. The effect of homogenizing on the properties of the alloy after extrusion is analyzed. Stress-strain response under cyclic loading at fixed plastic strain amplitude condition was examined by Hanet. al. [21] for age-hardenable Al:/7% Si:/0.4% Mg (A356) cast alloys and AA6063. The refined grain size, dendrite arm spacing (DAS) and unmodified acicular eutectic Si particles increased stress levels. The initial hardening occurred more rapidly and the stress amplitude reached the saturation stress in a quite early stage of the fatigue life, the same aging condition dependence was observed for the AA6063 alloy with no dendrite structure and eutectic Si particles. This indicated that nature of strengthening precipitates controlled the cyclic hardening behavior of the present cast alloys.

Siddiqui et. al. [22] studied various heat treatments of AA6063 aluminium alloy at under-aged, peak-aged and over-aged temperatures. The effect of precipitation on the tensile strength, yield strength, hardness, ductility and number of cycles required to fail the alloy at constant stress was investigated. They observed that the variation in time and temperature have improved the mechanical properties of the aluminum alloy, whereas the ductility has decreased. The scanning electron microscope (SEM) study of the under-aged alloy have exhibited facet fatigue fracture surface. Gupta et. al. [23] studied the precipitation and hardening potential of different metastable precursors in an Al:0.4%Mg:1.3%Si:0.25%Fe (wt.%) alloy with the help of differential scanning calorimetry (DSC), transmission electron microscopy (TEM) and hardness measurements. They observed that the hardness increase in a freshly solutionized alloy during natural ageing occurs primarily due to precipitation of clusters and zones, while peak hardness is achieved due to precipitation of β″ particles. The particles formed following β″ phase are not effective hardeners.

Gavgali et. al. [24] evaluated wear behaviour of age-hardened AA6063 aluminium alloy under dry sliding conditions. The as-cast and the aged samples were fully characterised before and after the wear testing using hardness, profilometer, scanning electron microscopy (SEM), optical microscopy, X-ray diffraction, and energy dispersive detector (EDS). The wear tests using on a pin-on-disc machine showed that the aging treatments improved the wear behaviour of AA6063 alloy compared to as-cast samples. Karamis et.al.[25]investigated the effect of cooling rate during homogenization treatment of AA 6063 aluminum alloy on the low-grade cold deformation–recrystallization properties. Experimental findings have shown that an increase in cooling rate caused an increase in critical strain and a decrease in maximum grain size.

The cyclic stress- and strain-amplitude-control fatigue response of aluminum alloy AA7055 is presented and discussed by Srivatsan[26]. Under total strain-amplitude control, the alloy showed evidence of softening to failure, the degree of cyclic softening increased with increasing temperature. For both stress- and strain-amplitude control fatigue, the macroscopic fracture mode was essentially identical, cyclic fatigue fracture on a microscopic scale revealed features reminiscent of locally ductile and brittle mechanisms. Low-cycle fatigue tests were performed in two AlMgSialuminium alloys with different chemical composition, namely AA6082-T6 and AA6060-T6 alloys and presented by Borrego et. al. [27]. The tests were undertaken in strain control with a strain ratio of $R_{\varepsilon} = -1$.The geometry of the hysteresis loops and the occurrence of Masing behaviour are also analysed. The observed behaviour is discussed in terms of the chemical composition of the alloys (Mg_2Si hardening particles and Mndispersoid content) and fracture mechanisms. Alloy AA6060-T6 exhibits nearly ideal Masingbehaviour, while alloy AA6082-T6 presents significant deviations from the Masingmodel. The type of cyclic deformation behaviour in AlMgSi alloys seems to be influenced by the dispersoid phase.

1.8.2 Low Cycle Fatigue of Metal Matrix Composites

Al-Si cast alloy reinforced by SiC-particulate with two different volume fractions has been investigated by Koh et al. [28] under strain-controlled conditions with and without tensile mean strains. The composites and the unreinforced matrix alloy showed cyclic hardening behaviour. The initial high tensile mean stress relaxed to zero for the ductile Al-Si alloy. Hall et al. [29] has reported the strain-controlled low-cycle fatigue (LCF) behaviour of AA2124/SiCp MMC.

Ding et al. [30] reported low cycle fatigue behavior of AA6061 aluminum alloy reinforced with Al_2O_3 particles in two volume fractions of 15% and 20%. They proposed a theoretical model based on fracture mechanics approach involving J-integral and crack tip opening displacement (CTOD) measurements. The results obtained from theoretical model was verified with that obtained experimentally using total strain-controlled symmetrical push-pull fatigue tests.

The effect of SiC volume fraction and particle size on the fatigue behavior of AA2080 alloy was investigated by Chawla et al. [31]. Increasing volume fraction and decreasing particle size resulted in an increase in fatigue resistance. Mechanisms responsible for this behavior are described in terms of load transfer from the matrix to the high stiffness reinforcement, and the decrease in strain localization with decreasing reinforcement interparticle spacing as a result of reduced particle size. Microplasticity was also observed in the composite. Intermetallic inclusions in the matrix acted as fatigue crack initiation sites. The effect of inclusion size and location on fatigue life of the composites is discussed. Hadianfard et al [32] studied the low cycle fatigue (LCF) resistance of two different AA6061 alloy reinforced with 20 vol% alumina particulate metal matrix composite. Both materials show three stages of response to LCF viz. initial fast hardening or softening in the first few cycles, gradual softening for most of the fatigue life, and a rapid drop in the stress carrying capability prior to failure. Both MMCs exhibit short LCF life which follows a Coffin-Manson relationship. All tested specimens demonstrate ductile fracture morphology at final failure. The experimental results are discussed in respect of strain amplitude, matrix composition and reinforcement shape and crack initiation.

Shang et al. [33] studied Micro-mechanisms of crack-tip shielding associated with the growth of fatigue cracks in metal-matrix composites with specific emphasis on the role of uncracked ligaments. Simple analytical models are developed for such bridging induced by both overlapping cracks and by coplanar ligaments. The predicted degree of shielding derived from these mechanisms is not large, but is found to be consistent with experimental observations in high-strength aluminum alloys reinforced with 15 to 20 vol % of SiC particles.

Muratoglu[34] investigated the SiC particulate reinforced aluminum metal matrix composites (MMCs) with pure aluminum by diffusion bonding process. The influences of SiC particulates with homogenization and age hardening on bonding properties of the joining quality of the Al/SiCp MMCs was studied. The application of aging before and after diffusion bonding decreases SiC particulate accumulation, and increases elemental concentration at interface.

Uygur et al. [35] usedpowder metallurgy processed metal matrix composites and performed fatigue testing under the strain control loading conditions. The influence of volume fraction (17 and 25 vol%), particulate size (2.5 and 15 μm) of reinforcement particles and strain ratio (R=0, R=0.5 and R= -1) are examined for AA2124+SiCp composite under T4 condition. The monotonic and cyclic stress-strain response of the AA2124 (25 vol% and 2.5 μm) composite was significantly altered by strain ratio values. Fatigue cracks frequently initiated from intensively stress concentrated regions. Increasing volume fraction and particle sizes resulted in early crack initiation.

Li et al. [36] studied low-cycle fatigue life and cyclic stress response of SiCp/Al–Si composites produced by spray deposition in comparison to the unreinforced alloy. Both the composite and matrix alloy display cyclic hardening under total-strain amplitude of 0.35–0.5%. Under low strain amplitude (0.3%), the Al–Si alloy shows cyclic. Stability after the initial hardening for 200 cycles. In contrast, the composite displays cyclic hardening immediately at the beginning of cyclic loading and a secondary hardening is also observed prior to fatigue fracture. Due to the higher density of pre-existing dislocations, interaction of mobile dislocations with the reinforcing SiC particles and more dislocation–dislocation interactions, a more pronounced strain-hardening behavior was observed for the composite, fatigue damage parameter indicates the inferior life in the low-cycle regime for the composite, compared to the unreinforced alloy. Fractographic analysis shows that particle/matrix debonding is the main mechanism of failure in the SiCp reinforced composite.

1.8.3 Micro structural investigation

Alan et al. [37] investigated the microstructure and fatigue properties of hydroformed sections of the AA5754 and AA6063 aluminum alloys and studied the microstructures of the alloys, with particular emphasis on the identification of second phase or constituent particles in the alloys. It was concluded that the higher fatigue lives of the AA5754 alloy compared to the AA6063 alloy in both the low- and high-cycle life regimes are due to the increased fatigue crack-initiation and propagation resistance of the AA5754 alloy and its probable cyclic strain-hardening behavior.

Sha et al.[38] Studies the microstructure of a model 6xxx series alloy by transmission electron microscopy (TEM), X-ray diffractometry (XRD) and differential scanning calorimetry (DSC). It was observed that α- AlFeSi andMg_2Si are formed during equilibrium solidification. DSC results confirm that β-AlFeSi is a metastable phase. SEM and TEM observations show that intermetallic particle size strongly depends on the Bridgman growth velocity. Quantitative XRD results show that the maximum proportion of metastable β-AlFeSi intermetallic phase is produced at relatively low growth velocities in the range of 30–60 mm/min. Both DSC and XRD analysis confirm that at higher growth velocities, such as 120 mm/min Mg_2Si phase is produced .

Tan[39] studied the microstructural and mechanical characterization of heat treatable 6xxx (Al-Mg-Si-Cu based) wrought aluminum alloys. The initial characterizations showed that Mg_2Si and $(Fe,Mn,Cu)_3$ $SiAl_{12}$ were the primary particles in the α-Al matrix. Nearly 140HB hardness was obtained with solutionizing at 530 ℃ and aging. Peak hardness is observed at optimum treatment of 175 ℃ for 8 hour.

1.8.4 Theoretical Analysis

Fatemi et al. [40] and Eleiche et al. [41] provided analytical analysis of rotating bending fatigue of a cantilever beam. They derived relationships to determine the surface strain amplitude, at the mid-point of the tested zone, as a function of the applied nominal bending stress, the vertical and horizontal deflections, and Young's modulus. They also presented a numerical methodology to calculate the rotating bending fatigue behaviour of a material from its cyclic stress-strain response and strain-life curve, and vice versa. The elasto-plastic solution for a circular cross-section was reported by Manson [42], and the reference stress method by Megahed [43]. These techniques stipulate a certain procedure to calculate the bending moment required to produce a prescribed surface strain (ε_s). From the prescribed surface strain amplitude, fatigue life can be established and similarly nominal bending stress (σ_b) from the calculated bending moment. Therefore, a curve can be plotted between the calculated nominal bending stresses and the corresponding fatigue life which is known as (S-N) curve. Comparisons between the values of σ_b show good correlation for beams with rectangular and circular cross-sections. Manson [42] showed that, under cyclic plasticity, the circular cross section bends about an axis, making an angle ϕ with the loading axis designated as the hysteresis angle, with the result that the cross-section deflects in both the vertical and horizontal directions. A modified energy-based approach was presented by Chiou and Yip [46] to predict the LCF lifetime of AISI 304 stainless steel by taking mean strain and stress effects into account.

1.8.5 Empirical Analysis

Eleiche et al. [41] conducted the low-cycle fatigue tests of rotating cantilevered notched beams under deflection controlled conditions. The cyclic stress–strain response and strain-life fatigue curves are determined. The effects of hardness, prestraining and machine allowance after heat treatment, on the fatigue life have also been studied.

Walker [45] conducted the low-cycle fatigue tests of rotating cantilevered beams under both load-deflection controlled conditions. From the knowledge of monotonic properties of the tested materials, the strain –life curves for these materials predicted by using modified universals slope equation and which is in excellent agreement with the corresponding experimental curves.

Megahedet. al [43] studied the rotating bending fatigue of cantilever beams analytically. Relationship are derived to determine the surface strain amplitude. A numerical methodology is also presented to calculate the rotating bending fatigue behavior of a material from its cyclic stress-strain response and strain-life curve and vice versa.

Fatemiet. al [40] presented the bi-linear log–log model to stress amplitude versus fatigue life data of 14 aluminum alloys. Life predictions of aluminum alloys based on linear and bi-linear models are compared and discussed.

1.8.6 Numerical Analysis

Barkanovet. al [49] briefly examined the objective of the aspects of the finiteelement analysis and thus to provide a basis for the understanding of the complete solution process. They discussed about three basic parts of finite element analysis. The first part comprises the formulation of FEM and the numerical procedures used to evaluate the element matrices and the matrices of the complete element assemblage. In the second part, methods for the efficient solution of the finite element equilibrium equations for static and dynamic analyses are discussed. In the third part of the course, some modelling aspects and general features of some Finite Element Programs (ANSYS, NISA, LS-DYNA) are discussed.

Szustaet. al [50] studied the fatigue damage accumulation model to analyze fatigue life of structure elements operating in conditions of multi axial, non-proportional low-cycle loadings. The damage variable depends on the stress damage accumulation function and the increments of plastic non-dilatational strain. The components of the stress and strain tensor in the conditions of complex low-cycle loadings were determined using constitutive relations and the law of kinematic hardening. The model was verified experimentally for EN AW-AA2007 aluminum alloy. The model can be used for practical engineering calculations after its further verification in the complex loading state for other structure materials.

Saraevet. al[51] have performed 3D Finite element calculations of axisymmetric problem to predict quantitatively the tensile behaviour of composites reinforced with ceramic particles aligned in stripes. It is indicated that varying the distance between the stripes when particle volume fraction is kept constant significantly influences the overall mechanical behaviour of composites. Whereas during elastic deformation 3D and axisymmetric formulations predict quantitatively similar results. The mechanical behaviour perpendicular to the stripe direction predicted by 3D and axisymmetric models may differ depending on the inclusion volume fraction.

Aghdam [52] investigated the Metal Matrix Composite materials using finite element micro-mechanical models. Initial yield and collapse envelopes have been generated for a Silicon Carbide-Titanium MMC for biaxial and shear loading. An analytical micro-mechanical model has been developed using the method of cells to predict the collapse behaviour. The results of the analytical model compare reasonably well with those of the finite element method.

Moraleda[53] studied the in-plane finite deformation of incompressible fiber-reinforced elastomers using computational micromechanics. Composite microstructure was made up of a random and homogeneous dispersion of aligned rigid fibers within a hyperelastic matrix. The simulations provided for the first time ‘‘quasi-exact’’ results of the in-plane finite deformation for this class of composites, which were used to assess the accuracy of the available homogenization estimates for incompressible hyperelastic composites.

Bosselliet al. [54] have presented a micromechanical understanding of the effects of clustering on short crack growth behaviour in Al–SiCp composites via finite element modelling. Consistent differences were identified between models with homogeneous versus clustered particle arrangements in terms of crack path morphologies and local crack–tip stress intensity fluctuations. Predicted influences of clustering on growth rates in the numerical models were found to be consistent with previous experimental results demonstrating that load transfer effects associated with changes in particle distribution may play a direct role in controlling the growth of short cracks in these materials.

1.9 Scope and Objectives of Present Work

It is observed from literature review that LCF analysis of AA6063 alloy and its metal matrix composite Materials (MMCs) are very few in available literature. To the best of knowledge no litereature is available for theoretical, numerical and empirical LCF analysis of this material which has tremendous industrial application as shown in Table 1.1. Thus the scope and objectives of present thesis are outlined below:

1. LCF analysis of as received AA6063-T6 alloy.
2. LCF analysis of heat treated AA6063-T6 alloy with different temperatures for same time.
3. LCF analysis of heat treated AA6063-T6 at same temperature and different times.
4. LCF analysis of AA6063-T6/SiCp MMCs
5. LCF analysis of AA6063-T6 with simply supported specimen.

1.10 Organization of the Thesis

The thesis work has been presented in nine chapters. The organization of the chapters in the thesis is given as below:

Chapter one introduces about fatigue, low cycle fatigue, aluminum alloys and in particular 6xxx series alloys, heat treatment, metal matrix composites, strain controlled method for LCF analysis, microstructural analysis and a detailed literature review about LCF analysis of aluminum alloys, their MMCs, heat treatments and theoretical, numerical and empirical LCF analysis.

Second chapter deals with the methodology used for low cycle fatigue analysis of AA6063 alloy using experimental, theoretical, empirical and numerical methods.

Third chapter deals with low cycle fatigue analysis of as received aluminum alloy AA6063-T6 for cantilever beam specimen to find out different fatigue parameters.

Low cycle fatigue analysis of heat treated AA6063 alloy at different temperatures to find fatigue parameters and see the effect of temperature on fatigue life has been presented in **fourth chapter.**

The effect of increasing time of heat treatment i.e. soaking time on low cycle fatigue has been presented in **fifth chapter**

Sixth Chapter deals with as-cast metal matrix composites for LCF analysis in room temper condition. The influence of volume fraction (2 and 8 vol%) of silicon carbide (SiC) reinforcement particles of particulate size of 400 mesh (37 µm) is examined.

In **chapter seven** the Low cycle fatigue (LCF) behaviour of aluminum alloy AA6063 of simply supported beam specimen has been investigated at room temperature condition. The influence of strain amplitude on the LCF behaviour of AA6063 in the normalized condition is presented. The tests were carried out at a constant strain rate of $2*10^{-3}$ s^{-1} and various strain amplitudes.

Chapter eight deals with microstructural analysis of fatigued samples using XR-D analysis, SEM and optical micrograph.

Conclusions and future scope of the work has been presented in **chapter nine.**

Finally all references are provided. Copies of published papers are also included at the end and certificates of submitted/under review papers are also listed.

1.11 Conclusions

The present thesis deals with Low Cycle Fatigue analysis of cantilever beam specimen made of AA6063-T6 alloy at room temperature condition, different heat treatment temperature and different soaking time and AA6063-T6/SiC metal matrix composite at room temperature condition and simply supported beam specimen at room temperature condition. A detailed literature review is presented in this chapter. Literature review shows there is still plenty of opportunity of research in the mentioned field. The investigation is also proposed to be performed theoretically, numerically and empirically. Next chapter deals with detail methodology that is adopted in this thesis.