

Experimental and numerical investigation of strain rate effect on low cycle fatigue behaviour of AA 5754 alloy

P Kumar¹ and A Singh¹

Department of Mechanical Engineering, IIT Patna, Bihta 801103, India

akhil@iitp.ac.in

Abstract. The present study deals with evaluation of low cycle fatigue (LCF) behavior of aluminum alloy 5754 (AA 5754) at different strain rates. This alloy has magnesium (Mg) as main alloying element (Al-Mg alloy) which makes this alloy suitable for Marines and Cryogenics applications. The testing procedure and specimen preparation are guided by ASTM E606 standard. The tests are performed at 0.5% strain amplitude with three different strain rates i.e. $0.5 \times 10^{-3} \text{ sec}^{-1}$, $1 \times 10^{-3} \text{ sec}^{-1}$ and $2 \times 10^{-3} \text{ sec}^{-1}$ thus the frequency of tests vary accordingly. The experimental results show that there is significant decrease in the fatigue life with the increase in strain rate. LCF behavior of AA 5754 is also simulated at different strain rates by finite element method. Chaboche kinematic hardening cyclic plasticity model is used for simulating the hardening behavior of the material. Axisymmetric finite element model is created to reduce the computational cost of the simulation. The material coefficients used for “Chaboche Model” are determined by experimentally obtained stabilized hysteresis loop. The results obtained from finite element simulation are compared with those obtained through LCF experiments.

Keywords: Strain controlled low cycle fatigue; Aluminum alloy 5754; Chaboche Model; Kinematic hardening; FEM

1. Introduction

The non-heat treatable wrought aluminium alloys are being used in aerospace, automobiles and marine applications due to their good combinations of specific strength, formability and good resistance towards corrosion [1, 2]. Among the various non-heat treatable aluminium alloys, Al-Mg alloys are extensively used due to good ductility, high strength to weight ratio and excellent corrosion resistance [Raynaud, Kaibyshev]. In past, corrosion resistance of 5xxx series alloys has been well studied by researchers [3, 4]. AA 5754 exhibits good tensile strength and corrosion resistance due to solid-solution strengthening of 3.4 wt% Mg [1]. Al-Mg alloys have majority of applications in components of aircraft, automobiles, cryogenic fields etc.

During service tenure, machine components are exposed to numerous types of cyclic loading. These include i.e. symmetric and asymmetric loading. When components are subjected to cyclic loading/unloading over a long period of time, it undergoes fatigue failure. The cyclic loading leads to plastic straining in localized regions which results in fatigue cracking of components. This eventually leads to failure of the component. Therefore, their cyclic behavior and low cycle fatigue properties need to be examined for safety reasons. Experimental evaluation of low cycle fatigue (LCF) behaviour



of aluminium alloys is of great importance and it is widely reported in the literature. Several authors have contributed their work on investigations of fatigue behaviour under stress and strain controlled conditions on various ferrous and non-ferrous alloys.

Tian et al. [5] have investigated the low-cycle fatigue (LCF) behaviour on different heat treated cast A319 alloy at different strain amplitudes. They found that fatigue life of peak aged alloy is quite higher compared to other treated conditions. Yun-rong et al. [6] have reported LCF behavior of high strength structural steel at different strain rates ranging from $(4 \times 10^{-5} - 0.12) \text{ sec}^{-1}$ under constant $\pm 1\%$ strain amplitude. They observed the decrease in fatigue life of material with increase in strain rate. Other works, such as Nandy et al. [7] studied the influent of heat treatment on LCF behavior on Al-Mg-Si alloy and Hao et al. [8] reported strain ratio effects on low-cycle fatigue behavior of 2124-T851 aluminum. However, the investigations on the effect of strain rate on fatigue life of Al-Mg alloys are not reported in the literature. In the present study, the strain-controlled LCF behaviour of relatively new Al-Mg alloy, AA 5754 is evaluated at different strain rates. LCF behaviour of the AA 5754 is modelled using finite element method based software Abaqus. The results obtained by FEM simulation are compared with those obtained by LCF experiments. The finite element simulations are performed based on cyclic plasticity model “Chaboche Model” [9].

2. Experimental procedure

2.1. Aluminium alloy (AA 5754)

This aluminium alloy, AA 5754 has been received from Prestige Industries, Mumbai. The as received alloy was in the form of plate having dimension $670 \times 210 \times 25 \text{ mm}^3$. The chemical composition of the selected alloy is listed in Table 1. The listed compositions of this alloy are in weight (%) and confirmed by Inductive Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) test.

Table 1. Chemical composition of AA 5754

Composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt(%)	0.07	0.16	0.05-0.06	0.4	3.4	0.06	0.10-0.15	0.06-0.07	Rest

2.2. Mechanical testing

Various tests are executed to evaluate the mechanical properties of AA 5754. These tests are performed for as received condition. A pictorial view of experimental setup and testing procedure are discussed in the below section.

2.2.1 Tensile test. Uniaxial tensile test is performed on Instron 8802 tensile machine. Yield strength (YS), ultimate tensile strength (UTS) and elongation produced during tensile test are evaluated. Sub-sized tensile specimen having 25 mm gauge length is prepared by wire electric discharge machining (WEDM) according to ASTM E8 [10] testing standard. The test was conducted at strain rate $6.66 \times 10^{-4} \text{ sec}^{-1}$. All results presented here are average of three test results.

2.2.2. Charpy impact test. WEDM is used to prepare the impact test specimens according to ASTM E23 [11] testing standard. The specimen dimension is kept $10 \text{ mm} \times 10 \text{ mm}$ cross section having 2 mm deep, 45°V notch and 0.25 mm lip radius at the centre of specimen.

2.2.3. Hardness test. Vickers hardness (H_V) was evaluated at 2 kgf load and $10X$ magnification on micro hardness tester. ASTM E92 [12] testing standard is used to evaluate the hardness of the as received alloy. Hardness is measured on mechanically polished specimen at four different positions and their average value is presented.

2.2.4. Low cycle fatigue test. The LCF test is performed on a fully automated, closed loop, servo-hydraulic test machine (Model Instron 8802). The specimen preparation and testing procedure is guided by ASTM E606/E606M standard [13]. The flat specimen of 5.5 mm thickness and gauge length of 16 mm is prepared from 25 mm thick plate using wire cut EDM machining. The schematic of standard LCF specimen is shown in Figure 1. The surface in-homogeneities, oxide layers and machined marks on the specimen acts as a localized stress riser, therefore well-polished specimen is prepared to perform these experiments. The specimen is subjected with strain control, symmetric tension-compression loading. A 12.5 mm strain gauge is used for measuring and controlling the strain in the specimen. Fully reversed cyclic loads are applied on the specimen with the strain ratio $R_E = \epsilon_{\min}/\epsilon_{\max}$ is kept at -1. In all LCF tests, strain amplitude of 0.5% strain is maintained. The test command signal exhibited a triangular waveform having zero mean strain. The testing frequency [14] is evaluated from the following relation

$$f = \frac{d\epsilon/dt}{4(\Delta\epsilon/2)} \quad (1)$$

where f is test frequency, $d\epsilon/dt$ is the strain rate and $\Delta\epsilon/2$ is the strain amplitude. The LCF tests are performed at three different strain rates of 0.5×10^{-3} , 1×10^{-3} and $2 \times 10^{-3} \text{ sec}^{-1}$ under constant strain amplitude of 0.5%.

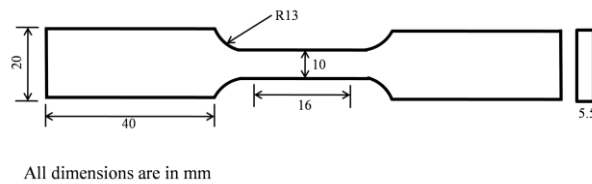


Figure 1. Schematic of LCF specimen

3. Numerical procedure

Finite element simulations are performed to model the LCF behaviour of AA 5754 by using Abaqus 6.12 commercial software package. The cyclic plasticity model “Chaboche kinematic” is used to simulate the hysteresis loop obtained from the strain controlled LCF test of the material. Axisymmetric finite element model is created to reduce the computational cost of the simulation. Chaboche kinematic hardening rule [9] is superposition of three Armstrong and Frederick model [15]. Chaboche postulates that the total back stress is summation of three back stresses. The material coefficients used with “Chaboche Model” are determined by experimentally obtained stabilized hysteresis loop. This model can be mathematically expressed as

$$dx = \frac{2}{3} c d\epsilon^p - \gamma x dp \quad (2)$$

Integral form of the above equation is given as

$$x = \frac{2}{3} \frac{c}{\gamma} (1 - e^{-\gamma \epsilon^p}) \quad (3)$$

where x is back stress vector, c kinematic hardening coefficient, γ is kinematic hardening exponent, $d\epsilon^p$ is plastic strain vector and dp is magnitude of plastic strain. c and γ are evaluated from stable

hysteresis LCF loop. In this model $\gamma x dp$ is the recovery or recall term and $2/3 c d\epsilon p$ is the linear hardening term.

$$dx = \sum_{i=1}^3 dx_i \quad (4)$$

$$dx_i = \frac{2}{3} c_i d\epsilon^p - \gamma_i x_i dp \quad (5)$$

According to this model, a stable hysteresis curve can be divided into three parts. First one, x_1 is modelling the initial high modulus at the onset of yielding. The second one, x_2 is modeling transient non-linear part of hysteresis loop. The last one, x_3 is for simulating the constant modulus part at higher strain range. The three decomposed hardening rule is used for improving the simulation of hysteresis loop. This model is widely used by various researchers for predicting the low cycle fatigue behaviour of different alloys [16-18]. Bari and Hassan [16] predicted the low cycle fatigue hysteresis loop of CS 1026 steel. Basantia et al. [18] have also used this model to characterize low cycle fatigue behaviour of different heat treated aluminium alloy 6063. Therefore in present study "Chaboche model" is used to simulate the strain hardening behavior of AA 5754.

4. Results and discussion

4.1. Experimental results

The tensile test results of AA 5754 are shown in Figure 2. The material properties, YS and UTS of the alloy are 191 MPa and 257 MPa respectively. The hardness, impact and tensile test results of this alloy are presented in Table 2 and they are already reported in the literature [21, 22]. The LCF tests are performed at laboratory environment and test setup used for experiments is shown in Figure 3. Figure 4 represents the peak stress achieved during entire cycle (fatigue life) at constant strain amplitude of 0.5% with three different strain rates. It is quite clear from Figure 3 that all alloy exhibit strain hardening behaviour at all strain rates. The similar behaviour of other Aluminium alloy is reported in the literature [14, 20]. The LCF test results are presented in Table 3. The highest fatigue life is obtained at lowest strain rate and minimum fatigue life is obtained at highest strain rate. It has been observed that the highest maximum stress of 288 MPa is achieved at strain rate of 1×10^{-3} . However the maximum peak stress at initial cycle is obtained when test performed at highest strain rate [20].

Table 2. Mechanical properties of as received AA 5754

Alloy Condition	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Impact Energy (J)	Hardness (H _v)
As received	191	258	10.98	28	81

Table 3. Fatigue life and peak stresses during LCF test

Strain rate (sec ⁻¹)	0.5×10 ⁻³	1×10 ⁻³	2×10 ⁻³
Fatigue life (cycles)	703	387	450
Peak stress (MPa)	263	288	271

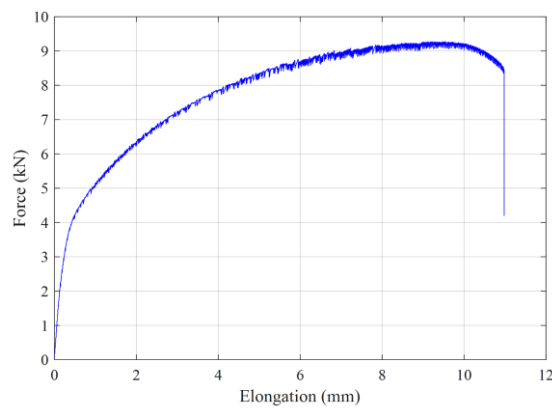


Figure 2. Load elongation curve from tensile test



Figure 3. Experimental setup for LCF test

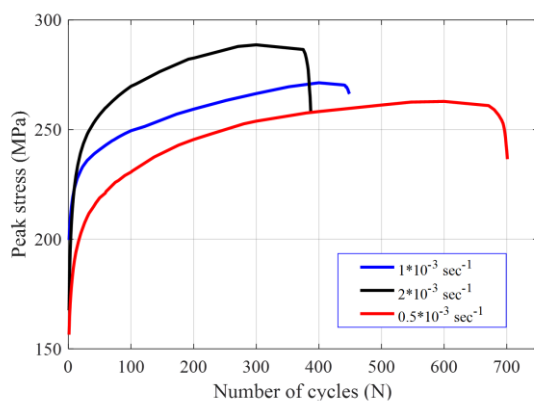


Figure 4. Comparative peak stress vs. number of cycles for all strain rates

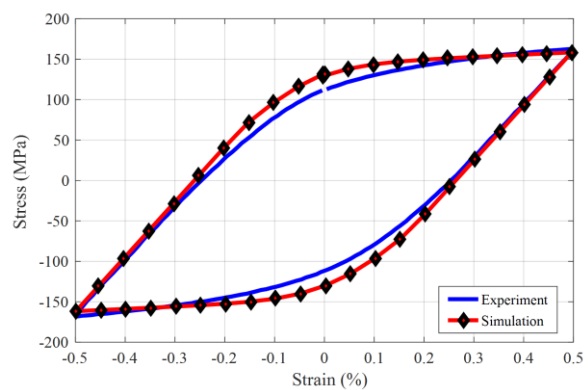


Figure 5. Comparison of experiment and simulated hysteresis loop at strain rate of $0.5 \times 10^{-3} \text{ sec}^{-1}$

4.2. Numerical results

Hysteresis loops obtained from experiments are modelled using FEM based software Abaqus (version 6.12). The chaboche model parameters are determined from the experimentally obtained stabilized loop [17, 23]. The stabilized loop is considered after half of the total number of experimentally obtained hysteresis loop. The material parameters are evaluated from experimentally obtained hysteresis loops are summarized in Table 4. The initial cycle of hysteresis loops are numerically obtained and they are presented in Figures 5-7. These material parameters can be used for simulating the LCF hysteresis loop for other strain amplitudes with corresponding strain rates. This signifies that the chaboche model can accurately simulate the LCF behaviour of Al-Mg alloy. The simulated hysteresis loops have same peak stress and strain values both in tensile and compressive directions are shown in Figure 5-7.

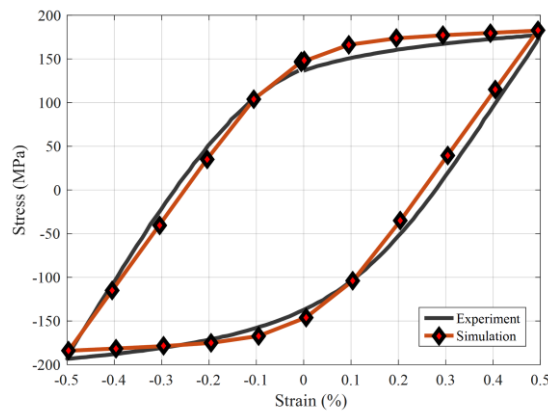


Figure 6. Comparison of experiment and simulated hysteresis loop at strain rate of $1 \times 10^{-3} \text{ sec}^{-1}$

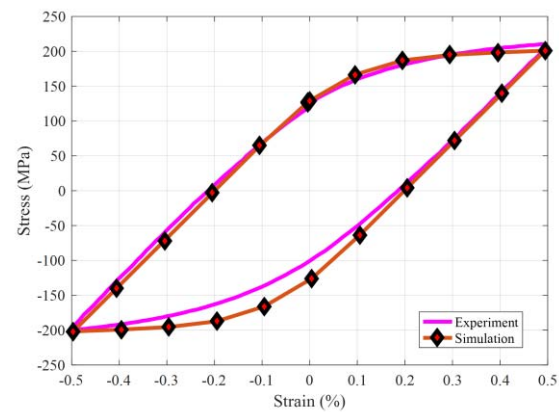


Figure 7. Comparison of experiment and simulated hysteresis loop at strain rate of $2 \times 10^{-3} \text{ sec}^{-1}$

Table 4. Material parameters determined from stabilized LCF cycle

Chaboche parameters	0.5×10^{-3}	1×10^{-3}	2×10^{-3}
σ_0 (MPa)	110	123	150
C_1 (MPa)	58500	62500	57500
C_2 (MPa)	57500	59500	58500
C_3 (MPa)	2300	2400	2300
γ_1	5700	5600	5600
γ_2	2800	1600	1800
γ_3	0	0	0
Q (MPa)	105	80	95
b	9.5	4.0	5.5

5. Conclusions

The strain controlled low cycle fatigue (LCF) behaviour of AA 5754 is studied at constant strain amplitude with three different strain rates. Cyclic hardening phenomenon is observed in the alloy at all the three strain rates. The highest fatigue life is obtained when test was conducted at lowest strain rate. The maximum peak stress at initial cycle is achieved at 1×10^{-3} strain rate. The LCF behaviour of the alloy is modelled by finite element method using Chaboche kinematic hardening cyclic plasticity model. The finite element simulations confirm good agreement with experimental hysteresis loops. This numerical simulation can be used for finding material behaviour and hysteresis loop where costly experimental facility is not available.

References

- [1] Van Horn, K. R. (Ed.). (1967). *Aluminum: properties, physical metallurgy and phase diagrams* (Vol. 1). American Society for Metals.
- [2] Davis, J. R. (1993). Aluminum and aluminum alloys. *ASM international*.
- [3] Raynaud, G. M., & Gomiero, P. (1997). The potential of 5383 alloy in marine applications. The Aluminum Association(USA), pp 351-364.
- [4] Kaibyshev, R., Musin, F., Lesuer, D. R., & Nieh, T. G. (2003). Superplastic behavior of an Al–Mg alloy at elevated temperatures. *Materials Science and Engineering: A*, 342(1), pp 169-177.
- [5] Tian, D. D., Liu, X. S., He, G. Q., Shen, Y., Lv, S. Q., & Wang, Q. G. (2016). Low cycle fatigue behavior of casting A319 alloy under two different aging conditions. *Materials Science and Engineering: A*, 654, pp 60-68.
- [6] Luo, Y. R., Huang, C. X., Tian, R. H., & Wang, Q. Y. (2013). Effects of strain rate on low cycle fatigue behaviors of high-strength structural steel. *Journal of Iron and Steel Research, International*, 20(7), pp 50-56.
- [7] Nandy, S., Sekhar, A. P., Kar, T., Ray, K. K., & Das, D. (2017). Influence of ageing on the low cycle fatigue behaviour of an Al–Mg–Si alloy. *Philosophical Magazine*, 1-26.
- [8] Hao, H., Ye, D., & Chen, C. (2014). Strain ratio effects on low-cycle fatigue behavior and deformation microstructure of 2124-T851 aluminum alloy. *Materials Science and Engineering: A*, 605, pp 151-159.
- [9] Chaboche, J. L. (1986). Time-independent constitutive theories for cyclic plasticity. *International Journal of plasticity*, 2(2), pp 149-188.
- [10] ASTM E8/E8M, Standard Test Methods for Tension Testing of Metallic Materials, American Society for Testing and Materials, 2009; West Conshohocken, PA
- [11] ASTM Standard E23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, 2007; West Conshohocken, PA
- [12] ASTM E92, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials, American Society for Testing and Materials, 2016; West Conshohocken, PA
- [13] ASTM E606/E606M-12, Standard Test Method for Strain-Controlled Fatigue Testing, American Society for Testing and Materials, 2012; West Conshohocken, PA
- [14] Borrego, L. P., Abreu, L. M., Costa, J. M., & Ferreira, J. M. (2004). Analysis of low cycle fatigue in AlMgSi aluminium alloys. *Engineering Failure Analysis*, 11(5), pp 715-725.
- [15] Armstrong, P. J. (1966). A mathematical representation of the multiaxial Bauschinger effect. *CEBG Report RD/B/N, 731*.
- [16] Bari, S., & Hassan, T. (2000). Anatomy of coupled constitutive models for ratcheting simulation. *International Journal of Plasticity*, 16(3), pp 381-409.
- [17] Paul, S. K., Sivaprasad, S., Dhar, S., & Tarafder, S. (2010). Cyclic plastic deformation and cyclic hardening/softening behavior in 304LN stainless steel. *Theoretical and Applied Fracture Mechanics*, 54(1), pp 63-70.
- [18] Basantia, S. K., Bakkar, M. A., Khutia, N., & Das, D. (2015). Simulation of LCF Characteristic of AA6063 Al Alloy Under Different Aging Conditions. *Materials Today: Proceedings*, 2(4-5), pp 2226-2235.
- [19] Han, W. Z., Chen, Y., Vinogradov, A., & Hutchinson, C. R. (2011). Dynamic precipitation during cyclic deformation of an underaged Al–Cu alloy. *Materials Science and Engineering: A*, 528(24), pp 7410-7416.
- [20] Fan, K. L., Liu, X. S., He, G. Q., Cheng, H., & Zhang, Z. (2015). Influences of strain rate on the low cycle fatigue behavior of gravity casting Al alloys. *Materials Characterization*, 107, pp 239-248.

- [21] Kumar, P., & Singh, A. (2017). Investigation of Mechanical Properties and Fracture Simulation of Solution-Treated AA 5754. *Journal of Materials Engineering and Performance*, 1-18.
- [22] Kumar, P., & Singh, A. (2017). Experimental and Simulation Study of AA5754 Tearing Energy. *Materials Today: Proceedings*, 4(2), pp 2711-2716.
- [23] Das, B., Bakkar, A., Khutia, N., & Das, D. (2017). Low Cycle Fatigue Performance Evaluation of TMT rebar. *Materials Today: Proceedings*, 4(2), pp 2554-2563.