International Journal of Fatigue 110 (2018) 130–143

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

The influence of metallurgical factors on low cycle fatigue behavior of ultra-fine grained 6082 Al alloy

N. Kumar[a,d], S. Goel[b], R. Jayaganthan[a,c,*], G.M. Owolabi[d]

[a] Department of Metallurgical and Materials Engineering, & Centre of Nanotechnology, Indian Institute of Technology Roorkee, Roorkee 247667, India
[b] Herbert Gleiter Institute of Nanoscience, Nanjing University of Science and Technology, Nanjing, Jiangsu, China
[c] Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India
[d] Department of Mechanical Engineering, Howard University, Washington, D.C. 20059, USA

ARTICLE INFO

Keywords:
Rolling
Al alloy
Strain amplitude
Low cycle fatigue
Ultrafine grains

ABSTRACT

In the present work, ultrafine grained Al 6082 alloy was produced by cryorolling (CR), room temperature rolling (RTR), CR + annealing (CR + AN) at 200 °C and RTR + annealing (RTN + AN) at 200 °C processes to study the effects of metallurgical factors (ultrafine grain structure, precipitates and secondary phase particles) on its low cycle fatigue behavior. Various characterization techniques such as the transmission electron microscopy, electron back scattered diffraction, scanning electron microscopy and differential scanning calorimetry were used to investigate the low cycle fatigue (LCF) behavior of the 6082 Al alloy. It was observed that the sample produced via CR + AN exhibits the highest LCF life when compared to the other samples investigated. The improvement in the LCF life of the 6082 Al alloy after CR + AN is attributed to the presence of small sized Si-rich precipitates, secondary phase particles, sub grains formation (200–400 nm) and high stored energy (32.16×10^{-4} J/mol).

1. Introduction

6082 Al alloy has been widely used for the fabrication of trusses, bridges, and automobile components due to its excellent combination of high specific strength (among the 6xxx series Al alloy), toughness, fatigue life, and corrosion resistance. There is an ever-growing demand to increase the performance of the Al alloys used in various light weight applications by significantly improving their mechanical properties through conventional thermo-mechanical processing. Hence, ultrafine grained materials produced by severe plastic deformation (SPD) have been an active area of research for the development of high strength materials. Cryorolling (CR) has been successfully used to produce ultrafine grained (UFG) materials at lower true strain when compared to the other SPD techniques [1–5]. CR is considered a potential technique for producing ultrafine grains in Al—Mg—Si alloys [1,2,5].

Most of the previous studies on UFG materials (that is materials with grain size in the range of 100 nm–1000 nm) were focused on investigating their monotonic strength. However, very limited attention has been given to the fatigue properties of the materials [6–9]. Fatigue can be classified as either (i) low cycle fatigue, LCF (i.e., fatigue life $< 10^3$ cycles) or (ii) high cycle fatigue, HCF (i.e., fatigue life $> 10^3$ cycles) [10], based on testing carried out at strain and stress controlled modes, respectively. It is well known that ductility and strength of alloys have considerable influence on their LCF and HCF life, respectively [7]. The UFG alloys exhibit favorable HCF life and trifling LCF life according to stress-life (S—N) and Coffin-Manson plots, respectively [11]. Apart from the Coffin-Manson and Basquin's models, the fatigue life of materials has been obtained using several other models [12–15]. However, none of these models is used to predict the fatigue life of UFG Al alloys. Research studies focusing on the LCF behavior of UFG alloy are also very scarce in open literature [16]. Ding. et. al. [17] proposed a new model to predict the life in the high cycle region as well as in the low cycle region but the model is too complex to predict the fatigue life of UFG materials. The LCF life of the materials was improved at the expense of the HCF life through proper annealing treatment as reported in the literature [18,11,12].

To prolong the service life of components, several surface treatments were adopted by various researchers. Chung et. al. [19] reported that 6061 Al alloy subjected to equal channel angular pressing (ECAP) showed fatigue resistance (high cycle) that is 10 times better than that of commercially available precipitation hardened AA6061-T6 alloy. This is due to fine-grained microstructure with low-grain boundary misorientation angles of the alloy produced via ECAP. Patlan et. al. [20] reported improved HCF strength but the decrease in LCF strength for

* Corresponding author at: Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India.
E-mail addresses: metarj@iitm.ac.in, rjayafmt@iitr.ernet.in (R. Jayaganthan).

https://doi.org/10.1016/j.ijfatigue.2018.01.018
Received 10 September 2017; Received in revised form 14 December 2017; Accepted 21 January 2018

the ECAP processed 5056 Al—Mg alloy compared to the alloy in O-temper condition. Lee et al. [21] observed a 15% improvement in the HCF strength for the 6061-T6 Al alloy subjected to ultrasonic nano-scale surface modification when compared to the alloy without surface modification. Laser shock processing (LSP) has been shown to improve the fatigue crack growth resistance of Al—Mg—Si alloy due to the highly tangled and dense dislocation arrangements [22]. LSP has also improved the HCF life of 6082-T651 Al alloy [23]. The enhancement of the fatigue life of AA 6082 Al alloy after laser-arc hybrid welding was attributed to low porosity, fine grain size, and high static strength of the weld [24]. Laser peening has also been reported to improve the fatigue crack growth resistance of 6061-T6 Al alloy [25]. The fatigue crack propagation resistance and consequently the fatigue life of 6056 Al alloy improved after local laser surfacing [26]. However, the effect of UFG and precipitates evolving out from Al-matrix during annealing on the LCF properties of Al—Mg—Si alloy has not been subjected to detailed study so far.

In the present work, the effects of UFG, secondary phase particles and precipitate on the LCF life of 6082 Al alloy produced via CR, room temperature rolling (RTR), CR followed by annealing (CR + AN) and RTR followed by annealing (RTR + AN) treatment were investigated. The microstructure of the processed alloy was characterized by scanning electron microscopy (SEM), electron back scattered diffraction (EBSD), and transmission electron microscopy (TEM) and the results were used to explain the experimentally observed LCF life. Differential scanning calorimetry (DSC) was also used to investigate the precipitates evolution and correlated with LCF properties.

2. Experimental procedure

The 6082-T6 Al alloy used for this study, with a chemical composition shown in Table 1, was procured from Hindalco India Pvt. Ltd, Mumbai, India. Homogenization of the alloy was performed at 550 °C for 24 h [27]. This was followed by CR and RTR of the Al alloy up to 1.38 true strain in order to produce ultrafine grains in the alloy. To maintain the liquid nitrogen and room temperature during processing, the samples were dipped for 3–5 min in liquid nitrogen and water before each pass in CR and RTR, respectively. The samples for the fatigue and tensile tests (shown in Fig. 1) were prepared according to the ASTM E 466-07 and the ASTM E8/M standards for investigating the fatigue and the tensile properties, respectively. Surface polishing was done to remove any surface defect from the sample following the standard procedure using a polishing cloth. Hardness testing was performed on Vickers hardness tester by applying 10 Kgf load for 15 s. The fatigue test was conducted at a frequency of 0.25 Hz and strain-ratio (R) = −1 at different strain amplitudes ranging from 0.2 to 0.55%. The tensile test was carried out after achieving 1000 cycles at a strain rate of 1 mm/min using Instron 8802 machine.

The CR & RTR Al alloy samples were annealed at 200 °C for 1 h to investigate the influence of precipitates on the fatigue life. The CR and RTR Al alloy after annealing are abbreviated in the present work as CR + AN (200 °C) & RTR + AN (200 °C), respectively. DSC was performed on Perkin Elmer Paris diamond instrument to study the precipitation kinetics of the Al alloy. Pure Al was used as a reference sample during the DSC analysis. The DSC scan was taken from 0 °C to 500 °C at a scan rate of 15 °C/min. The required dimensions of the samples for the DSC analysis (5 mm diameter) were prepared with the help of punching machine followed by polishing on emery paper. The final weight of the DSC sample was 30 mg. Kerosene oil was used to obviate the scratches during polishing on emery papers. The nitrogen gas was used to generate inert environment during testing and liquid nitrogen was used to cool down the furnace. After testing, base line correction was made, and testing of four samples for each of the four processing conditions was conducted to ensure the reproducibility of the test results.

Microstructural characterization of the processed samples was performed using electron back scattered diffraction (EBSD, FE-SEM Quanta 200) and transmission electron microscopy (TEM, TECHNAI 20G2-S-TWIN). The EBSD samples were prepared by mechanical polishing using emery papers (320, 800, 1200, 1500, and 2000) followed by cloth polishing. Furthermore, electro polishing using 20% perchloric acid + 80% methanol was performed on DC-Power supplier at 11 V, −20 °C and for 60–90 s. The step size given during EBSD scan was 0.05 µm. The grain dilation of the EBSD images was done to remove the unindexed point by applying the following conditions: (i) Grain tolerance angle, 5°, and (ii) Minimum grain size, 100 nm. The TEM samples were prepared by thinning down to 0.1 mm using mechanical polishing followed by punching (3 mm diameter punch was used) to make a circular disc of 0.1 mm thickness. Twin jet polishing of samples was subsequently carried out using etchant of 20% perchloric acid and 80% methanol for the TEM analysis.

Table 1
Chemical composition (wt%) of 6082 Al alloy.

Al	Si	Mg	Mn	Fe	Zn	Cu	Cr	Ti	Remaining
96.31	1.35	0.67	0.72	0.248	0.12	0.062	0.0698	0.045	Impurity

3. Results

3.1. Mechanical properties

3.1.1. LCF properties

The LCF tests of CR, RTR, CR + AN (200 °C) and RTR + AN (200 °C) samples were carried out at different strain amplitude ranging from 0.2% to 0.55% to achieve a maximum of 1000 cycles without failure as shown in Fig. 2 and Table 2. For the CR, RTR, and RTR + AN (200 °C) samples, 1000 cycles were successfully achieved only up to 0.4% strain amplitude, whereas for the CR + AN(200 °C) samples, 1000 cycles were achieved up to 0.5% strain amplitude. The maximum fatigue cycles at 0.55% strain amplitude for CR, RTR, CR + AN (200 °C) and RTR + AN (200 °C) samples are 470, 360, 845 and 540 cycles, respectively.

3.1.2. Hardening and softening behavior

To investigate the influence of strain amplitudes on the hardening or softening behaviors of the CR, RTR, CR + AN (200 °C) and RTR + AN (200 °C) samples, the maximum stress is plotted against the number of cycles as shown in Fig. 3. The RTR sample showed softening of sample till the end of testing. The RTR + AN (200 °C) sample showed softening till the end of testing at high strains (0.35%–0.55%), while at low strains (0.2%–0.3%), the sample showed initial hardening followed by softening till the end of testing. The CR and the CR + AN (200 °C) samples showed hardening followed by softening till the end of testing at all strain amplitudes as shown in Fig. 3.

3.1.3. Hysteresis loop

The hysteresis loop (stress-strain curve) for CR, RTR, CR + AN (200 °C) and RTR + AN (200 °C) samples just after the first cyclic loading at 0.55% strain amplitude is shown in Fig. 4 (a & b). It can be seen from Fig. 4(a) that during cyclic loading at 0.55% strain amplitude, the size of the hysteresis loop of the RTR sample is larger than that of the CR sample. After annealing at 200 °C, the size of the hysteresis curve for the RTR sample is also larger than that of the CR sample as shown in Fig. 4(b).

3.1.4. Monotonic strength after 1000 cycles

The monotonic strength of the samples after 1000 cycles have been achieved at different strain amplitudes from 0.2% to 0.5% are shown in Fig. 5. It can be seen from Table 2 that the maximum strengths achieved for CR, RTR, CR + AN (200 °C) and RTR + AN (200 °C) were 365 MPa, 345 MPa, 362 MPa and 349 MPa, respectively. It can also be seen that