Experimental Investigation of Fatigue Behavior of CR and RTR 6082 Al-alloy

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Abstract

In past few years, a lot of attention has been given for the development and application of aluminum-silicon-magnesium alloys due to their high strength to weight ratio, low density, and good resistance to fatigue crack growth. These alloys are attractive materials for application in advanced aerospace structures at low temperature. Therefore, the present study is envisaged to examine fracture-fatigue behavior of aluminum-silicon-magnesium alloy i.e. 6082-Al alloy. Plate shape 6082 Al-alloy is rolled at room temperature and cryogenic (liquid nitrogen) temperature for 40% and 70% thickness reductions. The effect of cryorolling on high cycle fatigue behavior of aluminum 6082 alloy has been examined through experimental investigation. The fatigue life and fatigue crack growth mechanism of the 6082 Al-alloy are evaluated through testing. Cryorolled and room temperature rolled Al-alloy, examined under HCF regime, shows a significant enhancement in fatigue strength as compared to bulk Al-alloy.

1. Introduction

Polycrystalline materials having the ultrafine grained microstructure show improved mechanical properties as compared to the conventional bulk materials (Gholinia et al., 2002). Literature shows that the superior mechanical properties are obtained through severe plastic deformation technique (SPD), which is widely used for obtaining ultrafine grained micro-structures in the metallic materials (Valiev et al., 2000; Valiev, 2003; Lowe and Valiev, 2004).

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Due to the high stacking fault energy, it is very difficult to produce the ultrafine grain structure from the aluminum alloy using conventional processing. To overcome this difficulty, SPD process such as equal channel angular pressing, multiple compressions, accumulative roll bonding, torsional straining and rolling area are available which are used to produce bulk nano-structured or ultrafine grained materials for structural applications (Panigrahi and Jayaganthan, 2008). These methods require large plastic deformations. By deforming at cryogenic temperature, nano-structured or ultrafine grained are produced from its bulk form (Mughrabi et al., 2004; Vasudevan et al., 1997). Due to the suppression of dynamic recovery, density of accumulated dislocations reaches at high immovable state during cryorolling of alloys (Xu et al., 1991). In ultrafine grained structure, the dislocation cells reconstruct themselves along with high angle grain boundaries (Nowotnik et al., 2007).

The 6000 series aluminium alloys are commonly used as medium strength structural materials; in particular, this series alloys are widely utilized as a general-purpose structural material due to their excellent formability and corrosion resistance. This series alloy having the properties such as low density, high strength to weight ratio, ductility, toughness and good resistance to fatigue. However, there is no previous reported literature on high cycle fatigue and fatigue crack growth rate (FCGR) (Nikolaos et al., 2013) cryorolled 6082 Al-alloy. The main purpose of the present work is to observe the effect of cryorolling on fatigue life and fatigue crack growth resistance of 6082 Al-alloy. The fatigue strength of cryorolled (CR) and room temperature rolled (RTR) Al-alloy is strongly dependent on grain size. FCGR study is performed under tension-tension fatigue loading using compact tension (CT) specimen of CR and RTR materials (Cadenas et al., 2009). On the basis of present investigation, a significant improvement in fatigue crack growth resistance has been observed for CR and RTR 6082 Al-alloy, which is due to the effective grain refinement in the alloy. The FE-SEM fractographs of the fatigue samples, fractured under fatigue loading, reveal the transition in fracture morphology from the high to low stress region.

2. Experimental Procedure

The starting thickness for 6082 aluminum alloy samples is taken as 10 mm. The 6082 Al-alloy with the chemical composition of 1.2 Si, 0.78 Mg, 0.5 Mn, 0.3 Fe, 0.14 Cr, 0.08 Cu, 0.05 Zn and rest is Al in the form plate of 50 mm thickness is machined into small plates. It is then solution treated (ST) by heating up-to 540°C and maintaining the temperature for approximately 2 hrs followed by quenching treatment in water at room temperature (Aginagalde et al., 2009). The solution treated Al 6082 alloy plates are subjected to rolling at cryogenic temperature to achieve 40% and 70% thickness reduction. The samples are soaked in liquid nitrogen for 15 minutes prior to each rolls pass during the rolling process. The diameter of roller is 110 mm and the rolling speed is 8 rpm. In each pass, the temperature before and after rolling of the sample is -190°C and -150°C, respectively. It is noted that the time taken for rolling and putting back the samples into the cryocan is less than 40 to 50 seconds during each pass in order to preclude the temperature rise of the samples. The solid lubricant, MgSi₂ has been used during the rolling process to minimize the frictional heat. A schematic diagram of cryorolling is shown in Figure 1. The thickness reduction per pass is about 5% but many passes are given to achieve the required thickness reduction. In order to further improve the mechanical properties, ageing is done for 14 hrs at 160°C.

Fig. 1. Schematic diagram of cryorolling process.
Fatigue tests are performed for bulk, room temperature rolled and cryorolled 6082 Al alloy as per ASTM E647-08 standard on a computer controlled 100 kN servo hydraulic Instron machine. The dimension of fatigue specimen is shown in Figure 2. The thickness ($t$) of the specimen is varied for bulk, 40% and 70% rolled samples. Clevis loading fixture is used for fatigue loading of specimen. Load ratio ($R=P_{\text{min}}/P_{\text{max}}$) for fatigue testing is taken as 0.2. The maximum and minimum loads are taken tensile. The frequency of the load is taken 20 Hz. The initial and final crack sizes are taken as 17 mm and 24 mm, respectively.

Fig. 2. Schematic diagram of fatigue specimen.

3. Results and discussion

The microstructure of the bulk Al-alloy exhibits lamellar grains having average grain size of around 77 $\mu$m, lying parallel to the ingot axis (Kumar et al., 2013). In case of CR samples, the grain size is reduced to about 700 nm and 620 nm for 40% and 70% thickness reductions, respectively, whereas the grain size is reduced to about 950 nm and 600 nm for the RTR samples subjected to 40% and 70% thickness reductions, respectively (Kumar et al., 2013).

An improvement in mechanical properties has been seen after cryorolling and room temperature rolling in comparison to starting bulk alloy. Table 1 shows the effect of cryorolling on tensile and hardness properties of the alloy (Kumar et al., 2013).

| Form of Alloy | Yield strength, $\sigma_{\text{YS}}$ (MPa) | Tensile strength, $\sigma_{\text{UTS}}$ (MPa) | % Elongation |
|--------------|------------------------------------------|------------------------------------------|-------------|
|              | CR           | RTR         | CR          | RTR         | CR    | RTR |
| 40% rolled   | 414.4        | 345         | 423.3       | 392.5       | 16    | 13  |
| 70% rolled   | 527          | 402.5       | 570         | 432.4       | 15.5  | 13.06 |
| Bulk alloy   | 260.3        | 340         |             |             | 12    |     |

3.1 Fatigue Analysis

The high cycle fatigue study is performed on a 100 kN servo-hydraulic machine to obtain a plot of stress with number of cycles. A typical fatigue specimen, prepared as per ASTM E647-08 standard, is shown in Figure 2 along with its dimensions. The fatigue tests for bulk, 40% CR, 70% CR, 40% RTR, and 70% RTR alloy are performed by taking a stress ratio ($R$) of 0.2. Thickness ($t$) of the fatigue specimen prepared from bulk, 40% CR, 70% CR, 40% RTR and 70% RTR alloy is taken as 5 mm, 6 mm, 3 mm, 6 mm and 3 mm, respectively. Table 2 presents the fatigue failure cycles along with corresponding alternating stress for bulk, 40% CR, 70% CR, 40% RTR, and 70% RTR alloy. Figure 3 also describes the alternating stress against the number of cycles to failure for bulk, CR and RTR samples. From the experimental results, the fatigue life is found to be $1.02 \times 10^5$ and $4.5 \times 10^7$ cycles corresponding to the alternating stress ($\sigma_a$) of 86.7 and 45.3 MPa, respectively, for the bulk material. In case of 40% CR alloy, the failure life is found to be $3.20 \times 10^5$ at $\sigma_a = 88.9$ MPa and $7.3 \times 10^6$ cycles at $\sigma_a = 56.3$ MPa, whereas in case of 70% CR samples, the fatigue life is found as $3.60 \times 10^7$ cycles at $\sigma_a = 177.8$ MPa and $7.82 \times 10^8$ cycles at $\sigma_a = 88.9$ MPa. The fatigue life of 40% RTR alloy samples is obtained as $3.10 \times 10^5$ and $6.80 \times 10^8$ cycles at $\sigma_a$ equal to 88.9 and 52.3 MPa, respectively, whereas the fatigue life of 70% RTR alloy samples is observed to be $3.46 \times 10^5$ and $7.82 \times 10^8$ cycles at $\sigma_a$.
equal to 166.7 and 55.5 MPa, respectively. From the results presented in table 2 and figure 3, it is seen that there is a significant improvement in the fatigue life after rolling. The fatigue life gradually improves with the amount of thickness reductions in both CR and RTR samples. In case of CR material, the improvement in fatigue life is found more as compared to RTR material for same amount of thickness reduction. The fatigue life of 70% CR samples is found maximum for a given value of alternating stress.

| Number of Failure Cycles | Bulk Alloy | 40% CR | 70% CR | 40% RTR | 70% RTR |
|-------------------------|------------|--------|--------|---------|---------|
| 1.02x10^5               | 86.7       | ---    | ---    | ---     | ---     |
| 1.50x10^5               | 80.0       | ---    | ---    | ---     | ---     |
| 1.65x10^5               | 73.3       | ---    | ---    | ---     | ---     |
| 3.10x10^5               | 66.7       | ---    | ---    | 88.9    | ---     |
| 3.20x10^5               | 60.0       | 88.9   | ---    | 83.3    | ---     |
| 3.46x10^5               | 53.3       | 86.1   | ---    | 77.8    | 166.7   |
| 3.60x10^5               | 46.7       | 83.3   | 177.8  | 72.2    | 155.5   |
| 4.50x10^5               | 45.3       | 77.8   | 166.7  | 72.2    | 144.4   |
| 5.30x10^5               | ---        | 72.2   | 155.5  | 61.1    | 133.3   |
| 6.30x10^5               | ---        | 66.7   | 144.4  | 55.5    | 122.2   |
| 6.80x10^5               | ---        | 61.1   | 133.3  | 52.3    | 88.9    |
| 7.30x10^5               | ---        | 56.3   | 111.1  | ---     | 77.8    |
| 7.60x10^5               | ---        | ---    | ---    | 100.0   | ---     | 66.7    |
| 7.82x10^5               | ---        | ---    | ---    | 88.9    | ---     | 55.5    |

Fig. 3. Alternating stress vs number of failure cycles for bulk alloy, 40% CR, 70% CR, 40% RTR, and 70% RTR alloy.

3.2 Fracture Surface Morphology

After fatigue testing, the fracture surfaces of bulk, CR and RTR specimens are examined through the FE-SEM as shown in Figure 4. The fracture surface of the bulk sample shows the transgranular ductile fracture. The dimple size is gradually decreasing with the increase in thickness reduction. In case of 40% CR samples, the fracture is seen with sufficient plastic deformation under normal mode. In case of CR 70% Al alloys, the fully ductile fracture surfaces are observed with micro-voids. The dimple size is reduced to less than 1 μm in 70% CR sample. Quasi cleavage fracture and secondary crack growth is clearly observed in 40% RTR sample. In 70% RTR sample, ductile fracture and fatigue striations are observed on the fractured surface.
3.3 XRD Analysis

The XRD peaks of starting bulk, CR and RTR alloy for different thickness reductions are shown in Figure 5. The presence of Fe-rich (Al_2FeSi) and Mg-rich (Mg_2Si) impurity phases can be seen in bulk alloy. The amount of (AlFeSi) is much lower in cryorolled material as compared to its bulk form, which is due to solution treatment given prior to cryorolling. The suppression of dynamic recovery due to cryorolling causes accumulation of higher density of dislocations. At room temperature, cryorolled materials containing high dislocation density may facilitate the nucleation of the precipitates due to the higher driving force available at this temperature. The peak of Mg_2Si is observed in bulk and 40% CR alloy but this peak is reduced in 70% CR and 70% RTR samples, which is due to heavy deformation strain imposed in the sample at cryogenic temperature.
4. Conclusions

In the present work, the high cycle fatigue behavior and fracture surface morphology of CR and RTR 6082 Al alloy have been investigated through experimental tests. The bulk alloy samples are rolled at different percentage of thickness reductions at room temperature and cryogenic (liquid nitrogen) temperature. The samples prepared from rolled alloy are tested under cyclic (tension–tension) loading. This study shows a significant improvement in strength and fatigue properties and a major reduction in fatigue crack growth rate for both CR and RTR alloy samples. The improvement in fatigue life is found more in case of CR samples as compared to RTR samples for same amount of thickness reduction. XRD analysis shows the peak of Mg₂Si in bulk and 40% CR alloy but this peak is reduced in 70% CR and 70% RTR samples, due to deformation strain induced in the sample at the cryogenic temperature. Fractographs of all tested samples signifies a transition in fracture morphology from dimpled rupture at the high stress level to ductile striations at low stress level.

References

Aginagalde, A., Gomez, X., Galdos, L., Garcia, C., 2009. Heat treatment selection and forming strategies for 6082 aluminum alloy, Journal of Engineering Materials and Technology 131, 044501-5.

Cadenas, P., Amrouche, A., Mesmacque G., Joziak K., Puchi-Cabrera, E., 2009. Influence of residual fatigue damage on the fracture toughness parameters of an AA6082-T6 aluminium alloy. Fatigue & Fracture of Engineering Materials & Structures, 33, 54-65.

Gholinia, A., Humphreys, F.J., Prangnell, P.B., 2002. Production of ultra-fine grain microstructures in Al–Mg alloys by conventional rolling. Acta Materialia 50, 4461-4476.

Kumar, V., Singh, I.V., Mishra, B.K., Jayaganthan, R., 2014. Improved fracture toughness of cryorolled and room temperature rolled 6082 Al alloys, Acta Metallurgica Sinica (Accepted)

Nowotnik, G.M., Sieniawski, J., Wierzbinska, M., 2007. Intermetallic phase particles in 6082 aluminum alloy, International Scientific Journal 28, 69-76.

Mughrabi, H., Hoppel, H.W., Kautz, M., 2004. Fatigue and microstructure of ultra-fine grained metals produced by severe plastic deformation, Scripta Materialia 51(8), 807-812.

Nikolaos, A., Antonis S., John C., 2013. Dynamic fracture toughness of Al–7Si–Mg (A357) aluminum alloy. Mechanics of Materials 58, 55-68.
Panigrahi, S.K., Jayaganthan, R., 2008. A comparative study on mechanical properties of Al 7075 alloy processed by rolling at cryogenic temperature and room temperature. Materials Science Forum, 584-586, 734-740.

Lowe, T.C. and Valiev, R.Z., 2004. The use of severe plastic deformation techniques in grain refinement. JOM, 64-77.

Valiev, R.Z., Islamgaliev, R.K., Alexandrov, I.V., 2000. Bulk nano-structured materials from severe plastic deformation, Progress in Material Science, 45, 103-189.

Valiev, R.Z., 2003, Paradoxes of severe plastic deformation. Advanced Engineering Materials, 5, 296–300.

Vasudevan, A.K., Sadananda, K., Rajan, K. 1997. Role of microstructures on the growth of long fatigue cracks. International Journal Fatigue, 19 (93), 151-159.

Xu, Y.B., Wang, L., Zhang, Y., Wang, Z.G., and Hu, Q.Z., 1991. Fracture behavior of an aluminum-lithium Alloy 8090-T6 at ambient and cryogenic temperature. Metallurgical Transactions A, 22A, 723-729.

ASTM E647-08 Standard Test Method for Measurement of Fatigue Crack Growth Rates, doi:10.1520/E0647-08E01