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Fatigue behaviour and crack growth rate of cryorolled Al 7075 alloy

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ABSTRACT

The effects of cryorolling (CR) on high cycle fatigue (HCF) and fatigue crack growth rate behaviour of Al 7075 alloy have been investigated in the present work. The Al 7075 alloy was rolled for different thickness reductions (40% and 70%) at cryogenic (liquid nitrogen) temperature and its tensile strength, fatigue life, and fatigue crack growth mechanism were studied by using tensile testing, constant amplitude stress controlled fatigue testing, and fatigue crack growth rate testing using load shedding (decreasing ΔK) technique. The microstructural characterization of the alloy was carried out by using Field emission scanning electron microscopy (FESEM). The cryorolled Al alloy after 70% thickness reduction exhibits ultrafine grain (ufg) structure as observed from its FESEM micrographs. The cryorolled Al 7075 alloys showed improved mechanical properties (Y.S, U.T.S, Impact energy and Fracture toughness are 430 Mpa, 530 Mpa, 21 J, 24 Mpa m$^{1/2}$ for 40CR alloy) as compared to the bulk 7075 Al alloy. It is due to suppression of dynamic recovery and accumulation of higher dislocations density in the cryorolled Al alloys. The cryorolled Al alloy investigated under HCF regime of intermediate to low plastic strain amplitudes has shown the significant enhancement in fatigue strength as compared to the coarse grained (CG) bulk alloy due to effective grain refinement. Fatigue crack growth (FCGR) resistance of the ufg Al alloy has been found be higher, especially at higher values of applied stress intensity factor ΔK The reasons behind such crack growth retardation is due to diffused crack branching mechanism, interaction between a propagating crack and the increased amount of grain boundaries (GB), and steps developed on the crack plane during crack-precipitate interaction at the GB due to ultrafine grain formation.

1. Introduction

Polycrystalline materials with ultrafine-grained (ufg) microstructure exhibit enhanced mechanical properties as compared to the conventional bulk materials [1]. Due to the ever-growing demand for superior mechanical properties of Al alloys, a new processing route, namely severe plastic deformation technique (SPD) has been used extensively to produce this alloy with the ultrafine-grained microstructures due to the limitation of conventional processing [2,3]. The processing of bulk aluminum alloys to ultrafine grain sizes through the conventional route is very difficult due to its high stacking fault energy. SPD processes such as equal channel angular pressing (ECAP), multiple compression, accumulative roll bonding, and torsional straining are used to produce bulk nanostructured/ultrafine-grained metals for structural and functional applications. However, majority of these methods require large plastic deformations with strains much larger than unity. Nanostructured/ultrafine grained pure metals such as Cu, Al, Ni [4–6] and Al [7–10] alloys are produced from its bulk metals/alloy by deforming them at cryogenic temperature using cryorolling technique. Rolling of pure metals and alloys in cryogenic temperature suppresses dynamic recovery and the density of accumulated dislocations reaches a higher steady state level and with the increasing number of cryorolling (CR) passes, these dislocation cells rearrange themselves into ultrafine-grained structures with high angle grain boundaries as reported in the literature [2,11].

The development of high strength Al alloys for aerospace and automobile applications is ever growing for extending life period of the structural components fabricated from these alloys. The aluminum alloys (7XXX) have been widely used as structural materials due to their excellent properties such as low density, high strength to weight ratio, ductility, toughness, and resistance to fatigue [12–14]. The cryorolled (CR) Al 7075 alloy exhibited improved tensile, hardness, impact properties compared to room temperature rolled Al alloy as reported in the earlier work done by our research group [10,15]. Increased fracture toughness of the cryorolled Al alloy, observed in our earlier work [16] was due to high density

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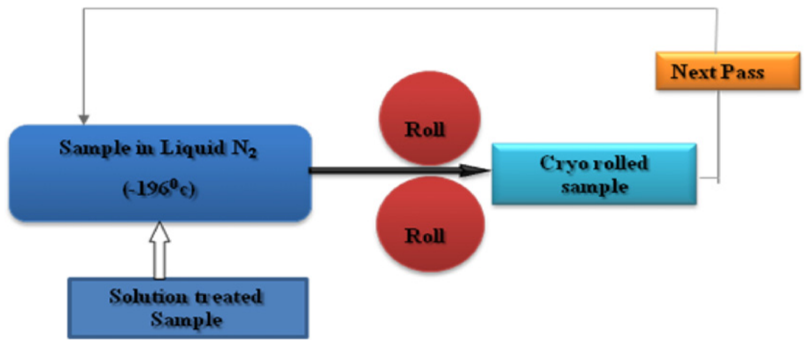

Fig. 1. Schematic diagram of cryorolling process.

of dislocations, ultrafine grain formation, grain boundary sliding, and increased fracture stress (σ_f). The effect of grain size on cyclic plasticity, fatigue life and crack growth rate of materials such as steel, copper, nickel, titanium and magnesium based alloys has been reported [17–19]. Two major conclusions based on these studies are drawn such as (i) the fatigue limit of pure fcc metals with relatively high stacking fault energy and wavy slip behaviour are not affected by the grain size; (ii) the fatigue strength of materials exhibiting planar slip, increases with decreasing grain size and follows the Hall–Petch relationship in the same way as the yield stress in conventional polycrystalline metals [20]. However, there is no reported literature on high cycle fatigue and fatigue crack growth rate (FCGR) of cryorolled Al 7075 alloy. Therefore, aim of the present work was to study the effect of cryorolling on fatigue limit and fatigue crack growth resistance of Al 7075 alloy. The fatigue strength of cryorolled Al alloys is strongly dependent on grain size similar to the yield strength as observed in the present work. The improved fatigue life and endurance limit has been observed in case of ufg Al 7075 alloy. FCGR tests were carried for tension–tension fatigue loading using compact tension (CT) specimens of ufg Al alloy. A significant improvement in fatigue crack growth resistance was observed for ufg Al alloy in the stage II region of Paris curve as compared to bulk Al alloy, due to effective grain refinement. SEM characterization of the samples fractured under fatigue loading has been carried out to reveal the transition in fracture morphology from the high to low stress region. Measurement of striation spacing has been carried out by using SEM images for FCGR tested samples, to investigate the crack growth resistance obtained experimentally.

2. Experimental procedure

The Al 7075 alloy with the chemical composition of 6.04 Zn, 3.64 Mg, 1.76 Cu, 0.50 Cr, 0.2 Si, 0.15 Mn, 0.57 Fe, and Al balance in the form of extruded ingot with the diameter of 50 mm, used in the present work, has been procured from Hindustan Aeronautics Ltd., Bangalore, India. The as received Al extruded ingot was machined into small plates and then solution treated (ST) at 490 °C for 6 h followed by quenching treatment in water at room temperature. The solution treated Al 7075 alloy plates were subjected to rolling at cryogenic temperature to achieve 40% and 70% thickness reduction. The samples were soaked in liquid nitrogen taken in the cryocan for 30 min prior to each roll pass during the rolling process. The diameter of the rolls and the rolling speed were 110 mm and 8 rpm, respectively. The temperature before and after rolling of the samples was −190 °C and −150 °C, respectively, in each pass. It may be mentioned that the time taken for rolling and putting back the samples into cryocan was less than a 40–50 s during each pass in order to preclude the temperature rise of the samples. The solid lubricant, $MoSi_2$, has been used during the rolling process to minimize the frictional heat. The thickness reduction per pass was 5% but many passes were given to achieve the required reduction of the samples. A schematic diagram of the cryorolling process is shown in Fig. 1.

Vicker's macro hardness and tensile tests were performed to determine the mechanical properties of the CR Al 7075 alloy subjected to various % reductions achieved by cryorolling treatment. Vickers macro hardness (H_V) was measured on the plane parallel to longitudinal axis (rolling direction) by applying a load of 15 kg for 15 s. The tensile test was performed after polishing the samples prepared in accordance with ASTM Standard E-8/E8M-09 [17] sub-size specifications parallel to the rolling direction with a 25 mm gauge length in air at room temperature using a S series, H25K-S materials testing machine operated at a constant cross-head speed with an initial strain rate of 5×10^{-4} s^{-1} [15]. XRD analysis was carried by Bruker AXS D8 advance instrument using Cu Kα radiation for identifying the presence of different phases in the staring bulk alloy and cryorolled samples.

Fatigue life characterization in terms of nominal stress (*S*–*N* curve characterization) was performed using a 100 kN servo hydraulic material testing machine at a cross-head speed of 3 mm/min under load control condition. In the tensile range, sinusoidal load cycles at a stress ratio of $R = 0.2$ and at a frequency of 20 Hz were used for all the tests. The samples for fatigue testing were machined along longitudinal axis of the supplied extruded ingot for the bulk 7075 alloy and along rolling direction in case of ufg alloy, according to ASTM E 468-04 and E 466-07 [21,22] and tested in air. The sample dimensions are shown in Fig. 2(a). Prior to testing, in order to minimize the introduction of residual stresses throughout the machining operation of the specimens, the samples were polished in air at room temperature. It enabled the elimination of the remaining circumferential notches that could act as stress concentrators during the fatigue tests.

Fatigue crack growth rate (FCGR) tests have been carried out on as-received and cryorolled Al 7075 alloy, as per ASTM E647-08 [23] standard and the sample dimensions are shown in Fig. 2(b). For tension–tension fatigue loading of compact tension (CT) specimen, the clevis loading fixtures were used. For this type of loading, both the maximum and minimum loads are tensile, and the load ratio, $R = P_{min}/P_{max}$, is in the range of $0 < R < 1$. A ratio of $R = 0.1$ is commonly used for developing data for comparative purposes. Cyclic loading may involve various waveforms for constant-amplitude loading. A measure of the resistance of a material to crack extension is expressed in terms of the stress intensity factor. Initially, the specimens were fatigue pre-cracked to either 0.1 B or h or 1.0 mm, whichever is greater and then growing the pre-crack under given loading conditions (which includes frequency 20 Hz, load ratio 0.1, load amplitude 3 kN and initial and final crack sizes, 17 mm ($a/w = 0.34$) and 24 mm, respectively. Crack length was measured by means of travelling microscope. To facilitate easy crack length