Ratcheting fatigue behaviour of Al-7075 T6 alloy: Influence of stress parameters

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Abstract. The use of aluminium and aluminium based alloys are increasing rapidly on account of its high formability, good thermal and electrical conductivity, high strength and lightness. Aluminium alloys are extensively used in aerospace, automobile, marine and space research industries and are also put into structural applications where chances of fatigue damage cannot be ruled out. In the current work, it is intended to study the ratcheting fatigue behavior of 7075-T6 aluminium alloy at room temperature. This Al alloy is potentially used in aviation, marine and automotive components as well as in bicycle parts, rock mounting equipment and parts of ammunition where there is every chance of failure of the parts due to deformation caused by ratcheting. Ratcheting is the process of accruement of plastic stain produced when a component is subjected to asymmetric cyclic loading under the influence of low cycle fatigue. To accomplish the requirements of the projected research, stress-controlled cyclic loading experiments were done using a ±250 kN servo-hydraulic universal testing machine (Instron: 8800R). The effect of stress parameters such as mean stress and stress amplitude were investigated on the ratcheting behavior of the selected aluminium alloy. It was observed that, ratcheting strain increased with increase in the value of stress amplitude at any constant mean stress while a saturation in strain accumulation attained in the investigated material after around 10-20 cycles, under all test conditions. The analyses of hysteresis loop generated during cyclic loading indicate that the material exhibits cyclic hardening in the initial fifty cycles which gets softened in further loading up to about 70-80 cycles and finally attains a steady state. The increase in the ratcheting strain value with stress parameters happens owing to increased deformation domain during cycling. The cyclic hardening accompanied by softening is correlated with characteristic precipitation features of the investigated Al 7075 alloy.

1. Introduction

Aluminium is being used widely due to its high strength, lightness, high formability and good thermal and electrical conductivity. The metal and its alloys are used in automobile, aerospace, marine and space research industries and are also put into structural applications. The current investigation is done using AA7075-T6, an alloy of high strength and used for aircraft components and structural applications. The upper and lower receivers and extension tubes of high precision M16 rifles used for military applications are particularly made from this alloy. The 7XXX series alloy is a heat treatable
alloy series with Zinc as the major alloying element. The Zn (4-6 % of weight) and Mg (1-3 % of weight) present increases the strength of the alloy by forming strengthening precipitates but they also reduce the corrosion resistance. T6 refers to the process of solution heat treatment followed by artificial ageing. This improves the mechanical properties of the alloy. Solution heat treatment of the alloy was done at 470°C for 1 hour, followed by rapid quenching in water and finally artificial aging at 120°C for 24 hours, which was followed by air cooling up to room temperature [1].

When used as aircraft components, the structures are subjected to cyclic loading during landing and take-off and therefore the chief mode of failure is fatigue. Many research works has been done to investigate and thus prevent the fatigue failure of the engineering components. Fatigue can be of two type high cycle and low cycle fatigue. One particular type of low cycle fatigue is ratcheting. Ratcheting is the process of strain accumulation during asymmetric cyclic loading of metallic parts under application of non-zero mean stress at different stress amplitudes [2]. It deteriorates the performance of components as a result of collective effect of fatigue damage and buildup of permanent ratcheting strain, which leads to further development of fatigue damage by continuous thinning out of the components’ cross-sectional area, and their combined effect leads to premature failure of the material [3]. About in the year 1911, Bairstow [4] introduce a new phenomenon calling it cyclic creep phenomenon and started research on it. In this research, he studied effect of positive mean stress on the nature of strain accumulation under uniaxial cyclic stressing in steel. Thereafter in the decade of 1950s, came a burst of investigations to understand axial strain accumulation due to asymmetric uniaxial cyclic loading at elevated temperature [5-7] as well as room temperature [8-10]. Hassan and Kyriakides [11] examined ratcheting behavior of consistently hardenable and softenable materials under uniaxial cyclic loading and concluded that material qualities incorporate cyclic hardening/softening. Later in 1996, the effect of mean stress and ratcheting on the fatigue life of steel was described by Xia et al. [12]. After 2000 onwards numerous investigations have been done on various materials viz. metals, compounds, polymers, etc. to understand their ratcheting behavior. Kang et al. [13] in 2002 reported uniaxial cyclic ratcheting and properties of plastic flow of SS304 at the room as well as elevated temperature. Development of dislocation pattern and internal stresses during the cyclic creep process was reported by Gaudin and Feaugas [14]. Kang et al. reported that softening behavior material during cyclic loading increases the ratcheting strain with number of cycles and hardening behavior of material during cyclic loading decreases the ratcheting strain with increases the number of cycle [15].

However as per the knowledge of the current investigator, very limited research has been done to study the ratcheting fatigue behavior of Al-7075 T6 alloy. In the current study, ratcheting fatigue behavior of Al-7075 T6 alloy is investigated under different combinations of stress amplitude and stress mean. Experimental observation, which exhibits material’s cyclic hardening in the initial fifty cycles which gets softened in further loading up to about 70-80 cycles and finally attains a steady state, has been discussed.

2. Experimental Procedures

2.1. Material and Heat Treatment

The aluminium 7075 alloy was received in the form of rods of 16 mm diameter. The chemical composition of the alloy is given in Table 1. Solution heat treatment of the alloy was done at 470°C for 1 hour, followed by rapid quenching in water and finally artificial aging at 120°C for 24 hours, which was followed by air cooling up to room temperature [1].
2.2. Microscopic examinations and Hardness measurements
The cylindrical samples of 16 mm diameter with an approximate height of 10 mm were cut from the as received and heat treated materials for performing microstructural characterization and determining Vickers hardness. The samples were electro-polished using stainless steel rod as cathode and sample as anode with phosphoric acid as electrolyte, preheated to 70°C for 10 minutes at 100 mA/cm² current density and 12 V voltage. After washing the electro-polished sample with distilled water, these were etched using freshly prepared Keller’s reagent [2 ml HF (1%), 3 ml HCl (1.5%), 5 ml HNO₃ (2.5%) and 190 ml H₂O (95%)]. The microstructures of the investigated materials were examined using an optical microscope (Model: ZEISS Axiocam ERC 5s) connected to an image analyzer and a series of representative photographs were recorded. The hardness measurements of aluminium alloy were made at indentation load of 5 kgf and 10 kgf. These tests were carried out using a Vickers hardness testing machine (Leco, Model: LV 700, Michigan, USA) for a dwell time of 10 s.

2.3. Tensile and Fatigue Test
Al-7075 T6 samples were mechanically tested for tensile and fatigue properties. Round bar specimens, for tensile and fatigue tests having a gauge lengths of 25mm and 13 mm with diameters of 6 mm and 7 mm respectively were fabricated as per ASTM standards E8M and E-606 respectively. These tests were done on servo-hydraulic universal testing machine (Model: INSTRON 8800R). All tensile tests were carried out at a crosshead speed of 1mm/min. Samples for ratcheting tests were with very well surface finish. All these tests were done at a constant stress rate of 50 MPa/s. Whole tests carried on varying mean stress (σₘ) and stress amplitude (σₐ). A summary of the test conditions is shown in Table 2. Fractographic studies were carried out by using scanning electron microscope (Model: JEOL-JSM 6480LV).

3. Results and Discussion
As described above, the as received Al-7075 samples were subjected to T6 heat treatment. Optical microstructure of as received alloy is presented. Nature of hardness, tensile and ratcheting behavior of the sample after this heat treatment is presented below in a detail. All tests were performed at room temperature.

3.1 Microstructural analysis and hardness
Figure 1 reveals the microstructure of as received Al-7075 alloy. It consists of elongated pancake shaped grains of uniform size. The average grain was calculated using the

Table 1: Chemical composition of the investigated Al-7075 alloy

| Element | Zn   | Mg   | Cu   | Fe   | Cr   | Si   | Mn   | Al   |
|--------|------|------|------|------|------|------|------|------|
| Wt. %  | 5.203| 2.163| 1.856| 0.261| 0.256| 0.206| 0.087| Balance |

Table 2: Stress values for ratcheting tests.

| Sl. No. | σₘ/MPa | σₐ/MPa |
|---------|--------|--------|
| 1       | 55     | 25     |
| 2       | 65     | 25     |
| 3       | 75     | 25     |

Figure 1: Optical microstructure of 7075 alloy
linear intercept method and was found to be 11.76 ± 1.11 μm. The average hardness values for 5 kg load applied of as received and heat-treated alloy are 92 Hv and 150 Hv respectively and for 10 kg load applied are 95 Hv and 151 Hv respectively. The values of hardness for 5 kg load are graphed in Figure 2. The hardness values for as received alloy was observed to be lower than that of the T6 alloy at both loads. In T6 condition, a continuous uniform grain structure was observed (Fig.1). Kumar et al. concluded that there exists Al and Cu particle rich continuous fine grain structure in the alloy. In association, precipitates like MgZn$_2$ at the grain boundaries helps to increase the hardness value. The temperatures, time and cooling rate are important factors of aging treatment, which changes the properties of the alloy. Kumar et al. studied effect of post weld heat treatment on the hardness of AA7075. They reported that hardness value of the alloy was 170 VHN for T6 heat treated condition. The composition of the current alloy is similar with Kumar et al. and the hardness values also close to their results [16].

3.2 Tensile properties

The obtained tensile properties of the material are summarized in Table 3. These data were analyzed to calculate the value of yield strength, ultimate tensile strength (UTS), percentage uniform elongation ($\%\epsilon_u$) and percentage total elongation ($\%\epsilon_t$) of alloy. Typical engineering stress-strain curve is plotted which is shown in Figure 3.

![Figure 3: Engineering stress strain plot of Al-7075 T6 alloy](image)

| YS (MPa) | TS (Mpa) | $\%\epsilon_u$ | $\%\epsilon_t$ |
|----------|----------|-----------------|-----------------|
| 70       | 188      | 25.6            | 40.3            |

YS = yield strength, TS = tensile strength, UE = uniform elongation, TE = total elongation

![Figure 2: Hardness values of the as received as well as T6 samples.](image)

The fracture surfaces of broken tensile specimens were examined using field emission scanning electron microscope (FESEM, Model: Nova Nano SEM/ FEI). Typical fractographs obtained from the FESEM are shown in Figure 4. The fractographs reveals dimples on the surface, the typical nature of fracture surface of a ductile material, as expected. The dimple fracture in aluminium alloy was observed due to presence of second phase particles in it and there is de-cohesion of the particle – matrix inter phase. The fracture surface also indicates presence of some inclusion-like particles.
3.3 Ratcheting behaviour

In this section, the uniaxial ratcheting behaviour of the investigated alloy is discussed. The tests were carried out under different combinations of mean stress (σ_m) and stress amplitude (σ_a). Earlier investigations on ratcheting suggest that strain accumulation due to ratcheting attains a saturation value in the range of 50 to 100 cycles, after which the rate of accumulation of strain varies negligibly even up to failure of the material [17]. Keeping this feature into mind, all ratcheting tests in the current investigation were done up to 100 cycles, to understand the trend of strain accumulation in the investigated alloy under tension-tension mode.

3.3.1 Uniaxial ratcheting behavior with varying stress amplitude and at constant mean stress

The ratcheting strain accumulated in the alloy under various stress amplitude is shown in Figure 5. It was observed that at constant mean stress with increasing stress amplitude, accumulation of ratcheting strain increases.

![Figure 4: SEM micrographs of the fracture surface of the broken tensile sample](image1)

![Figure 5](image2)

Figure 5: Typical ratcheting strain versus no. of cycle of the investigated aluminium 7075-T6 alloy: (a) at constant σ_m = 55 MPa with varying σ_a = 25 MPa, 35 MPa and 45 MPa.(b) at constant σ_m = 65 MPa with varying σ_a = 25 MPa, 35 MPa and 45 MPa.(c) at constant σ_m = 75 MPa with varying σ_a = 25 MPa, 35 MPa and 45 MPa.
It was also deduced from the graphs that the saturation of strain accumulation occurs in the alloy after about 20 cycles for all the test conditions. Initially the accumulation of ratcheting strain is sharp up to 10 cycles, which slowed down after that and finally attainment of steady state takes place after 20 cycles, for all combinations of mean stresses and stress amplitudes. The increase in strain accumulation with increase in stress amplitude can be expressed as the variation in the height of the hysteresis loops which corresponds to the deformation zone. From the graph it is clear that with increase in stress amplitude the height of the hysteresis loop increases. This fact causes more strain in a particular cycle during the cyclic loading event. On reverse loading, a part of the gathered strain is recovered while a part of strain retains in the sample as to add in the measure of ratcheting strain. Considering the phenomenon of dislocation generation, more amount of dislocations generate due to increased maximum stress during loading with higher stress amplitude.

3.3.2 Uniaxial ratcheting behavior with varying mean stress and at constant stress amplitude

The ratcheting strain accumulated in the alloy under various stress mean is shown in Figure 7. It was observed that at constant stress amplitude with increasing mean stress, accumulation of ratcheting strain increases significantly as comparison to constant mean stress with varying stress amplitude.

4. Conclusions

Uniaxial ratcheting behavior of Al-7075 T6 alloy has been examined in this investigation. The following conclusions can be drawn from the experimental outcomes and their pertinent discussion.

(1) Strain accumulation due to ratcheting increases with increase in mean stress and/or stress amplitude for either of these is constant. This increase in strain accumulation occurs due to enhanced deformation zone during cyclic loading operations with higher stress amplitude, which thereby increases the remnant dislocation density.

(2) The analyses of hysteresis loops produced during cyclic loading indicate that the alloy exhibits cyclic hardening in the first fifty cycles. However it gradually softens on further cycling up to the
range of 70-80 cycles and lastly attains a steady state. This characteristic of softening in the range of 70-80 cycles is considered to be attributed to the formation of Al-Cu type precipitates in cyclic loading.

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