J Mater Sci (2010) 45:3067–3072
DOI 10.1007/s10853-010-4313-y

Fatigue properties of a modified 7075 aluminum alloy containing scandium

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Received: 15 September 2009 / Accepted: 10 February 2010 / Published online: 23 February 2010

Abstract Fatigue properties such as the fatigue strength, fatigue notch sensitivity, and fatigue crack propagation rate, of a modified Al-7075 + Sc aluminum alloy were investigated in this study. The effects of solution treatment on the fatigue performance of this alloy were also investigated. The ultimate tensile strength of the as-extruded sample was 705.5 MPa. The ultimate tensile strength decreased by 12% after solution treatment. The fatigue limit σ_e of the as-extruded sample decreased from 201.2 to 154.4 MPa after solution treatment. The fatigue notch sensitivity for the as-extruded and solution-treated (ST) samples was 0.97 and 0.64, respectively. The crack growth rate in the as-extruded sample with fine precipitates was clearly lower than that of the ST sample that had coarse precipitates at $R = 0.1$ when $\Delta K < 15$ MPa$\sqrt{m}$. However, the growth rates of both the samples were approximately the same when $\Delta K > 15$ MPa$\sqrt{m}$. The higher yield strength of the as-extruded sample led to a lower crack growth rate when compared to the ST sample.

Introduction

Aluminum that contains scandium has been shown to have excellent mechanical properties at room temperature due to the presence of very fine and coherent Al_3Sc precipitates, which can be effective obstacles to mobile dislocations. It can also stabilize fine-grain microstructures at high temperature [1, 2]. To date, there have been many studies on the effects of adding scandium to aluminum. These studies have mainly focused on precipitation [3], superplasticity [4], and recrystallization [5] in relation to the addition of scandium to aluminum alloys.

There have only been a limited number of studies, however, on the fatigue behavior of aluminum alloys that contain Sc [6–9]. In wrought Al–5Mg–0.3Mn–0.06Zr alloys [6], the addition of scandium reportedly contributed to a higher tensile yield strength, a higher fatigue strength, and a lower crack growth rate due to the presence of coherent Al(Sc, Zr) precipitates and a very fine subgrain structure. For an Al-5754 aluminum alloy modified with scandium and zirconium [7], fine coherent $Al_3Sc_{1-x}Zr_x$ precipitates had a positive effect on the alloy by inhibiting fatigue and a negative effect due to an increase in grain size, which is known to decrease fatigue resistance. The addition of scandium was reported to contribute to an overall increase in the fatigue strength of the aluminum alloy. However, detrimental or insignificant effects on fatigue strength due to the addition of scandium have been reported in aluminum alloys. For Al-7010 aluminum alloys with scandium addition [8], it was reported that the addition of scandium resulted in poor fatigue crack growth resistance and fatigue thresholds. For an Al–Mg–Sc alloy that contained Al_3Sc particles [9], no cyclic softening was observed in samples that had large Al_3Sc particles. However, samples with fine Al_3Sc particles showed cyclic softening at higher plastic-strain amplitudes due to the loss of particle strength through particle redissolution within strongly strained slip bands.

To date, there has been no attempt to evaluate the fatigue properties of a modified Al-7075 alloy that contains scandium. This alloy is suitable for aircraft and sports-

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related applications. Accordingly, the objective of this study is to investigate the fatigue properties, including fatigue strength, fatigue notch sensitivity, and fatigue crack growth rate, of a modified Al-7075 alloy that contains scandium. The effects of solution treatment on the fatigue performance of this alloy are also investigated.

Experimental procedure

The chemical composition of the modified 7075 Al aluminum alloy used in the present experiment is shown in Table 1. This alloy contains 0.1% Sc. Billets were hot extruded at 653 K in order to make a rectangular bar ($50 \times 50\ mm^2$) with an extrusion ratio of 8:1. The solution treatment was conducted at 743 K for 5 h and the alloy was then quenched in room-temperature water. The typical optical microstructure of the as-extruded and solution-treated (ST) materials is shown in Fig. 1a and b, respectively. As shown in Fig. 1a and b, elongated grains are observed in the extruded material, suggesting that recrystallization did not occur during or after hot extrusion. The solution treatment produced little change in the microstructure from the as-extruded condition. Microstructure observations were documented in detail in an earlier report [10].

For tensile and fatigue tests specimens, rods with a diameter of 10 mm and a length of 100 mm were extracted from the extruded rectangular bar in a longitudinal direction. Tensile specimens were machined with a gage length and a gage diameter of 45 and 5 mm, respectively, and a 20-mm shoulder radius. A displacement rate of 1 mm/min was used for tensile testing. Two different types of specimens were used for endurance fatigue testing (see Fig. 2). One had a plain surface (without any notch) (Fig. 2a), while the other had a blunt notch (Fig. 2b). Constant stress amplitude testing was conducted under axial loading with a zero mean stress (15-Hz frequency) in a servo hydraulic fatigue machine (Instron 8516) at room temperature.

Constant load amplitude fatigue crack growth experiments were carried out on a single edge-notched (SEN) sample with a thickness of 3 mm, a width of 25 mm, and a length of 100 mm using an Instron 8516 servo-hydraulic testing machine. Notch length of 3 mm was machined using wire EDM.

The specimens were tested under a load ratio $R = \sigma_{min}/\sigma_{max} = 0.1$ at a frequency of 15 Hz. The stress intensity factor for the SEN sample was calculated using the following equation [11]:

$$K = \left(\frac{P}{Wt}\right)(\pi a)^{0.5}\left\{1.12 - 0.231\left(\frac{a}{W}\right) + 10.55\left(\frac{a}{W}\right)^2 - 21.72\left(\frac{a}{W}\right)^3 + 30.39\left(\frac{a}{W}\right)^4\right\} \quad (1)$$

where W, t, and a are the width and thickness of the specimen and crack length, respectively.

Table 1 Chemical composition of the modified 7075 Al alloy

Alloy	Zn	Mg	Cu	Mn	Cr	Zr	Sc	Al
Al-7075 + Sc	5.2	2.0	0.3	0.3	0.03	0.11	0.1	Bal.

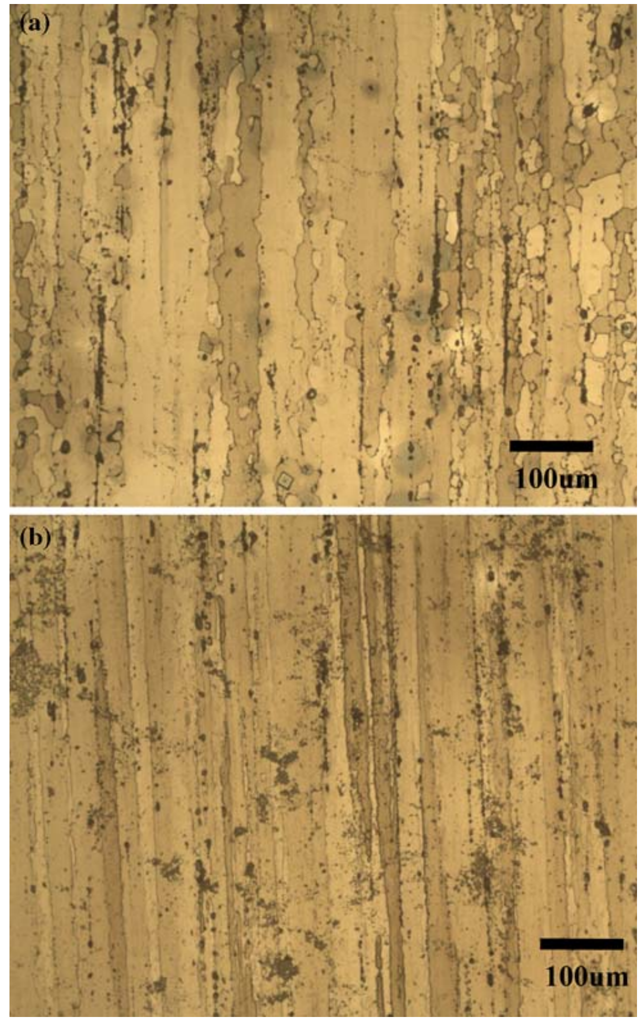

Fig. 1 Microstructures of **a** as-extruded and **b** solution-treated Al-7075 + Sc alloy

Results and discussion

Tensile behavior

The engineering stress–strain curves of the as-extruded and ST samples are shown in Fig. 3. The yield and ultimate

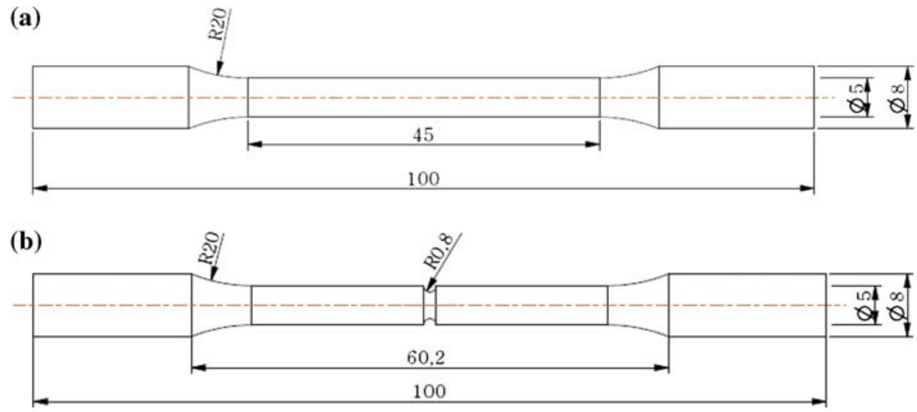

Fig. 2 Fatigue specimen and dimension are in mm: **a** smooth round bar specimens and **b** notched round bar specimen ($K_t = 1.83$)

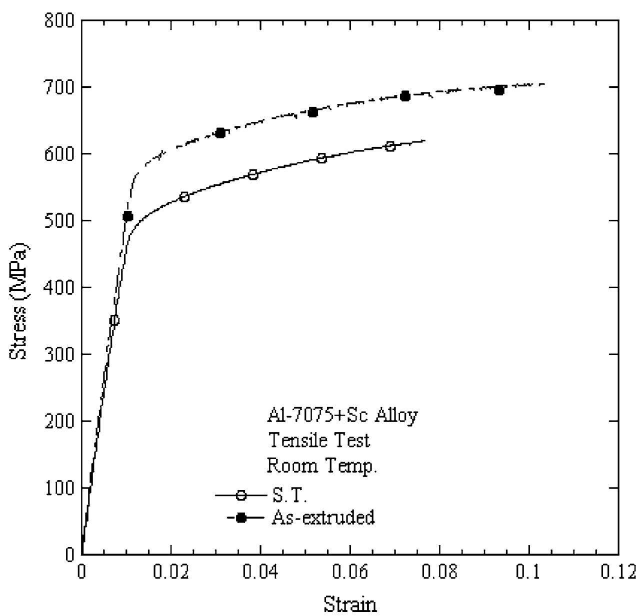

Fig. 3 Tensile stress–strain curves for the as-extruded and solution-treated (ST) Al-7075 + Sc samples

tensile strength of the as-extruded sample were 553.3 and 705.5 MPa, respectively. After solution treatment, the yield and ultimate tensile strength decreased by 13 and 12%, respectively. The tensile and fatigue test results of the as-extruded and ST 7075 + Sc aluminum alloys are summarized in Table 2, together with data from other investigations on Al-7000 alloys [8, 12]. The ultimate tensile strength of 705.5 MPa is much higher than those of 7000 series high strength aluminum alloys [8]. For example, the ultimate tensile strength of an Al-7010 alloy was reported elsewhere as 566 MPa [8]. The Sc-containing Al-7010 alloy exhibited a somewhat higher strength (=588 MPa) and ductility when compared to the conventional 7010 alloy [8]. The dramatic increase in the UTS of this as-extruded sample is attributed to a precipitation strengthening effect from the addition of scandium. The tensile elongation of the as-extruded and ST samples was 10.4 and 7.7%, respectively. The tensile elongation decreased by 26% after solution treatment. In our study, grain and precipitation coarsening and/or relaxation of internal stresses during or after solution treatment are responsible for the reduction of strength and ductility in the samples.

The strain hardening rate $d\sigma/d\varepsilon$, where σ is the true stress and ε is the true plastic strain, is shown in Fig. 4 as a function of nominal flow stress ($\sigma - \sigma_y$), where σ_y is the yield strength. It can be seen that the strain hardening behavior can be approximated by three regimes and that the strain hardening rate in the as-extruded sample is always greater than that in the ST sample. The initial hardening rate values of the as-extruded and ST samples are approximately 8300 and 4300 MPa, respectively. This initial rate represents the maximum hardening rate expected from dislocation storage. This value of the as-extruded sample is twice that of the ST sample, indicating that the higher initial dislocation density in the as-extruded sample created during extrusion might have contributed to the initial higher strain hardening. The initial strain hardening rates of the as-extruded and ST samples are 11 and 6% of the

Table 2 Mechanical properties of 7000 alloys

Material	σ_y (MPa)	σ_{UTS} (MPa)	σ_e (MPa)	σ_e/σ_{UTS}	ε_f (%)
As-extruded Al-7075 + Sc	553.3	705.5	201.2	0.29	10.4
Solution-treated Al-7075 + Sc	462.8	619.6	154.4	0.25	7.7
Al-7010 [8]	500	566	260	0.46	13
Al-7010 + Sc [8]	537	588	252	0.43	14
Coarse-grained Al-7075 [12]	502	545	158	0.29	12
Fine-grained Al-7075 [12]	461	514	216	0.42	16

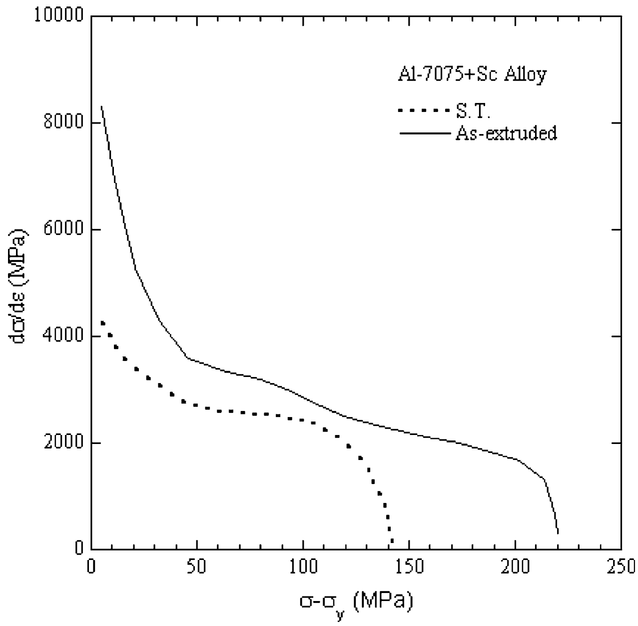

Fig. 4 The strain hardening rate of the as-extruded and solution-treated (ST) Al-7075 + Sc samples as a function of flow stress

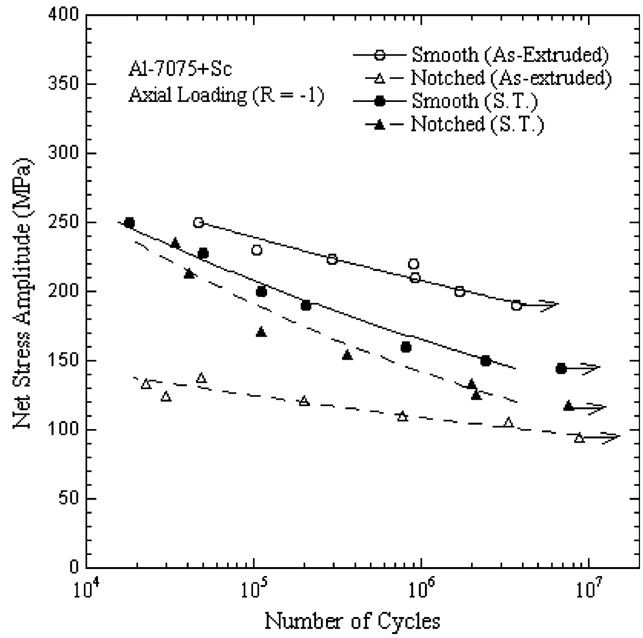

Fig. 5 S–N curves for the as-extruded and solution-treated Al-7075 + Sc samples

elastic modulus, respectively, values that are much larger than that of pure aluminum (=*E*/50) [13]. The strain hardening rate values decrease immediately after yielding, as shown in Fig. 4, with an increase in nominal flow stress for both the samples. For the ST sample case, there was a drop in the strain hardening rate, whereas for the as-extruded case, there was a gradual decline in the strain hardening rate as the applied stress increased.

Many dislocations created during extrusion and retained in the as-extruded sample may participate in annihilation rather than multiplication, which results in a rapid decrease of the strain hardening rate of the as-extruded sample. When the nominal flow stress exceeds approximately 50 MPa, the strain hardening rates of the as-extruded and ST samples gradually decrease with an increase in nominal flow stress. The slope of the as-extruded sample is close to that of the ST sample. The work hardening behavior of both the samples is almost identical due to similar dislocation annihilation effects. For both the cases, the final abrupt fall in the curves is likely to relate to damage processes that accelerated failure ahead of the onset of necking rather than to dislocation annihilation effects.

Fatigue strength

Figure 5 shows the S–N curves for the as-extruded and ST 7075 + Sc aluminum alloys with and without notches. The KaleidaGraph program was used for curve-fitting. Their S–N curves can be described by the following equations in units of MPa.

$$N = 4.2 \times 10^{47}\sigma_a^{-17.86} \quad \text{for smooth specimens (as-extruded)} \tag{2}$$

$$N = 2.4 \times 10^{47}\sigma_a^{-20.0} \quad \text{for notched specimens (as-extruded)} \tag{3}$$

$$N = 7.4 \times 10^{28}\sigma_a^{-10.31} \quad \text{for smooth specimens (ST)} \tag{4}$$

$$N = 4.9 \times 10^{23}\sigma_a^{-8.20} \quad \text{for notched specimens (ST)} \tag{5}$$

The results of the smooth bar tests are discussed first. As shown in Fig. 5, the fatigue limit σ_e of the as-extruded sample at $N = 2 \times 10^6$ decreased by 21% from 201.2 to 154.4 MPa after solution treatment. The fatigue strength is known to be a function of the ultimate tensile strength in metallic alloys. In general, the majority of fatigue life is known to be taken up by crack initiation rather than by crack growth in a high cycle regime. An increase of ultimate strength is therefore considered to enhance resistance to fatigue crack initiation, especially near the surface region, which serves as a crack nucleation sites. The values of the fatigue limit σ_e obtained for the as-extruded and ST samples are ~0.29 and 0.25 times the UTS value, respectively. These normalized values are close to that of the 7075 alloy (0.29 × UTS) [12]. Thus, it can be inferred that the reduced fatigue limit σ_e of the ST samples resulted from a reduction of the ultimate tensile strength due to solution treatment. The tensile and fatigue test results of the as-extruded and ST 7075 + Sc aluminum alloys are summarized in Table 2, together with data from other investigations on Al-7000 alloys [12].

The fatigue notch factor, K_f, is defined as follows.

$$K_f = \frac{\sigma_e}{\sigma_{en}} \quad (6)$$

where σ_e and σ_{en} represent the nominal fatigue limit of the minimum cross-sectional area for smooth and notched specimens, respectively. Based on the data in Fig. 5, the values of K_f for the as-extruded and ST samples were computed as 1.78 and 1.17, respectively. Values of fatigue notch sensitivity reflect the difference of the theoretical stress concentration factor from the fatigue notch factor. This difference is generally produced by notch-tip plastic relaxation. The theoretical stress concentration factor K_t for the notched specimen was determined to be 1.83 according to a fully elastic analysis by the finite element method. The ratio of K_f/K_t provides a measure of the fatigue notch sensitivity (the higher the ratio, the higher the notch sensitivity). The ratio of $K_f/K_t = 1$ indicates that a notch fully produces the theoretical reduction in the fatigue limit stress. The ratios for the as-extruded and ST samples were 0.97 and 0.64, respectively. Conclusively, it can be seen that the as-extruded sample is very sensitive to notching, and the value K_f/K_t is close to that of the wrought 6061-T6 alloy [14]. However, the ST sample had significantly lower notch sensitivity than the as-extruded sample.

Figure 6a and b shows fatigue fractured surfaces at the near surface region of the as-extruded and ST Al-7075 + Sc smoothed samples at $R = -1$, respectively. The surfaces shown in these figures were located at approximately 1-mm depth from the specimen surface. For the case of the as-extruded sample, the fractured surface shows many dimples and tears resulting from significant irregular plastic deformation, as shown in Fig. 6a. The ST sample exhibits relatively smoother fractured surfaces, compared to that of the as-extruded sample.

Fatigue crack growth behavior

Fatigue crack growth rate (da/dN) curves of the as-extruded and ST samples at a load ratio of $R = 0.1$ are presented in Fig. 7. The curves show that the ΔKth value for the as-extruded sample (=6.5 MPa$\sqrt{m}$) is slightly higher than that for the ST sample (=5.2 MPa$\sqrt{m}$), although the growth rate curves do not reach threshold levels experimentally at $R = 0.1$. These two values are slightly higher than that of the Al-7075-T651 alloy ($\approx$4.2 MPa$\sqrt{m}$) [15] and the Al-7010 + Sc alloy ($\approx$3.1 MPa$\sqrt{m}$) [8]. It is widely believed that the fatigue crack growth rate in the near threshold regime is dominated by both intrinsic features of the material (e.g., chemical composition, microstructure) and extrinsic testing conditions (e.g., test atmosphere, temperature, load ratio). The extrinsic testing conditions and chemical composition for all the specimens were unchanged.

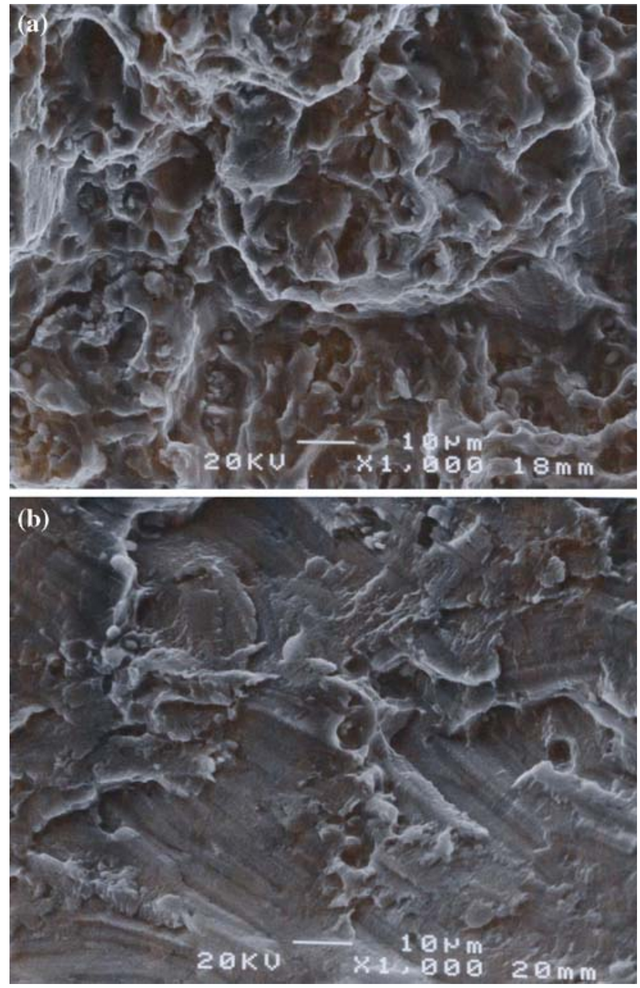

Fig. 6 Fatigue fractured surfaces of **a** the as-extruded and **b** solution-treated Al-7075 + Sc smoothed samples at $R = -1$

Thus, it can be inferred that the threshold stress is mainly influenced by the microstructure of the material. The tensile elongation of this alloy was lower after solution treatment due to grain growth. The lower toughness of the ST sample with larger grain size partially contributed to a lower crack growth resistance and lower threshold stress because of its inferior ability to accommodate plastic strain during cycling.

The crack growth rate in the as-extruded sample with fine precipitates is clearly much lower than that in the ST sample that had coarse precipitates at $R = 0.1$ when $\Delta K < 15$ MPa$\sqrt{m}$. However, the growth rates of both the samples are approximately the same when $\Delta K > 15$ MPa$\sqrt{m}$. The crack growth rate of the as-extruded sample is much lower than those of Al-7075-T6 alloys reported by other studies [16–18], as shown in Fig. 7.

While it is not clear why the as-extruded sample exhibited a lower crack growth rate, it might be due to the higher yield strength in the as-extruded sample. Assuming the crack growth per cycle is proportional to the crack tip opening displacement (CTOD) due to plasticity-induced

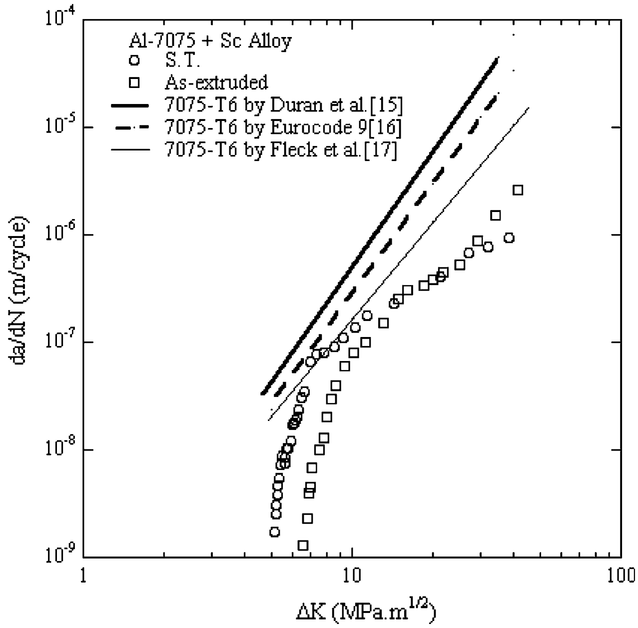

Fig. 7 Fatigue crack growth rates of the as-extruded and solution-treated (ST) Al-7075 + Sc samples at $R = 0.1$

crack closure, the crack growth rate can be described by the following equation [19]

$$da/dN \approx \Delta CTOD \approx \Delta K^2/\sigma_y E \quad (7)$$

where ΔK is the range of the stress intensity factor and E is Young's modulus. Higher yield strength causes smaller ΔCTOD of fatigue cracks under the same stress intensity factor condition. This may in turn lead to a reduction in the crack growth rates. Thus, the crack growth rate in the as-extruded sample, which has higher yield strength, was lower than that of the ST sample having lower yield strength in the Paris-law region. The higher resistance to crack growth of the as-extruded sample is also due to its higher yield strength, compared to Al-7075-T6 alloys [16–18]. Conclusively, the as-extruded sample with fine Al_3Sc particles exhibited higher ultimate tensile strength and yield strength, resulting in a higher resistance to crack growth and initiation, compared to the ST samples.

Conclusions

The tensile strength, fatigue strength, fatigue notch sensitivity, and fatigue crack propagation rate of modified Al-7075 + Sc aluminum alloys were investigated. The effects of solution treatment on the fatigue performance of this alloy were also investigated. The yield and ultimate tensile strength of the as-extruded sample were 553.3 and 705.5 MPa, respectively. After solution treatment, the yield and ultimate tensile strength decreased by 13 and 12%, respectively. The fatigue limit, σ_e, of the as-extruded sample decreased by 21% from 201.2 to 154.4 MPa after solution treatment. The fatigue notch sensitivity of the as-extruded and ST samples was 0.97 and 0.64, respectively. The crack growth rate of the as-extruded sample with fine precipitates was lower than that of the ST sample that had coarse precipitates at $R = 0.1$ when $\Delta K < 15$ MPa$\sqrt{m}$. However, the growth rates of both the samples were approximately the same when $\Delta K > 15$ MPa$\sqrt{m}$. The higher yield strength of the as-extruded sample caused a lower crack growth rate, compared to the ST sample. Conclusively, the as-extruded sample that had fine Al_3Sc particles exhibited a higher ultimate tensile strength and yield strength, resulting in a higher resistance to crack growth and initiation, compared to the ST samples.

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