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Low Cycle Fatigue behavior of AA7075 with surface gradient structure produced by Ultrasonic Shot Peening

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Abstract

Effect of ultrasonic shot peening (USSP) for different durations, with graded surface structures, was studied on low cycle fatigue behavior of the aluminium alloy 7075 (AA7075) at room temperature. LCF tests were conducted at different total strain amplitudes. Surface microstructures of the USSP treated specimens were characterized using X-ray diffraction and transmission-electron microscopy. No phase change was found due to USSP. Surface region of the ultrasonically shot peened sample was found to develop nanosize grains of 16-20 nm. Significant improvement was observed in LCF life of the specimen subjected to USSP for 180 seconds. However, LCF life of the sample USSPed for long duration of 300 seconds was reduced. The higher fatigue life resulting from USSP for 180 seconds, may be attributed to increased resistance of the USSPed sample against fatigue crack initiation, due to grain refinement in the surface region.

Keywords: Ultrasonic Shot Peening, Grain refinement, Low Cycle Fatigue, Fractography

1. Introduction

Fatigue known to be the single largest cause of failure of metallic components, leads to approximately 90% of all metallic failures therefore it has been the area of profound research interest. Fatigue life of structural components is known to be improved by introduction of compressive residual stress at the surface by delaying the process of crack initiation. Several methods are available to introduce beneficial surface compressive residual stresses [Luong et al. (2010)].

Ultrasonic shot peening (USSP) is a novel process of surface grain refinement to nano level and introducing compressive residual stresses in the surface region to increase the resistance of material against crack initiation [Los Rios et al. (1995)]. Ultrasonic shot peening is based on impingement of surface by vibrating spherical steel balls using high power ultrasonic waves. Piezoelectric transducer emits ultrasonic waves at 20 kHz, which are amplified using an acoustic booster. The waves pass through sonotrode to a housing, containing the balls. The balls vibrate inside the housing, strike the surface to be treated, get reflected from the surface and collide with others. Due to high

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frequency of the system, the surface of the specimen gets peened with large number of impacts over a short period of time. The process of USSP induces compressive residual stress field on the surface of the ductile materials. Since the plastic deformation region caused by shot peening is only about 200–300μm thick, an extremely high stress (strain) gradient develops [Xing et al. (2004)]. The depth of peening can be increased by increasing the duration of shot bombardment, peening with larger or higher velocity shots or both. However, increasing shot peening intensity increases roughness of the shot peened surface and the level of cold work at the surface. Both of these reduces fatigue performance [Peyre et al. (2000)].

In general, fatigue crack initiation occurs at the surface of the component. It is now well established that materials with fine grains have greater resistance against fatigue-crack initiation, whereas coarse-grained materials offer high resistance to fatigue crack propagation [Suresh (1991), Hanlon el al. (2003) and Mughrabi et. al (2004)]. Recently, ultrasonic shot peening (USSP)/ surface mechanical attrition treatment (SMAT) has been recognized as a potential process of producing gradient microstructure with nano-grains in the surface region progressively increasing in size from surface towards interior up to certain depth. USSP uses combination of peening parameters to multiply the kinetic energy resulting from impacts of balls, to generate a large number of defects like dislocations and interfaces (grain boundaries) in surface region of the treated part and consequent transformation of the initial microstructure into ultra-fine grains [Guagliano et a. (2012)].

The effect of nanostructured surface produced through USSP, has been studied on different properties in various alloys [Kumar et al. (2014), Pandey et al. (2015) and Rai et al. (2014)]. However, its effect on LCF behavior has not yet been fully explored. The objective of the present investigation was to study the effect of ultrasonic shot peening (USSP) on microstructure in the surface region and LCF behavior of the AA7075.

2. Experimental

The AA7075 used in the present investigation was procured from the Hindalco Industries, Renukot, India, in form of a cylindrical bar. The chemical composition of the alloy determined by spark emission spectrometer is presented in Table 1. The material was used in retrogressed and re-aged condition (RRA). It was solution treated at 470°C for 0.5 h, pre-aged at 120°C for 24 h and subjected to retrogression at 200°C for 10 mins, followed by secondary ageing at 120°C for 24 hrs.

Table 1. Chemical Composition of Aluminium Alloy 7075

Element	Zn	Mg	Cu	Si	Fe	Mn	Al
Wt %	4.89	2.123	1.52	0.33	0.007	0.09	Bal.

Ultrasonic shot-peening treatment of the AA7075 was performed with steel balls of 3mm diameter at vibrating amplitude of 80μm for 30 (USSPed 30), 60 (USSPed 60), 180 (USSPed 180) and 300 (USSPed 300) seconds. Optical metallography of the un-USSPed specimens was carried out to characterize the initial microstructure following mechanical polishing and etching with Keller's reagent at room temperature. A Rigaku X-ray diffractometer with Cu Kα radiation was used to determine phase constitution, average crystallite size and mean micro strain of the USSPed specimen. Crystallographic structure of the USSPed samples was characterized by XRD in 2θ range from 30° to 90°. TEM foils of the USSP treated surface layer were prepared by sectioning a thin slice, close to the shot peened region, followed by mechanical polishing and subsequent electro chemical polishing in an electrolyte of 20% nitric acid in methanol at -28°C at applied voltage of 20V. Transmission electron microscopy was carried out using TECNAI 20 G^2 operating at 200 kV. LCF tests were conducted on a servo hydraulic MTS^{TM} under completely reversed total strain control mode.

3. Results and discussion

3.1. Microstructure of un-USSPed specimen

The optical micrograph of the heat treated sample shows the well-established microstructural features like the dark phases of intermetallic Al_7Cu_2Fe and Mg-rich precipitates in the α-phase matrix (Fig. 1 a), the small black precipitates with white boundaries $MgZn_2$ (Fig. 1 b) and the black precipitates without any white boundaries as Mg_2Si, both surrounded by dark colonies of Al_7Cu_2Fe [Andreatta et al. (2004)]. The average grain size of the AA7075 was 78μm in un-USSPed condition.

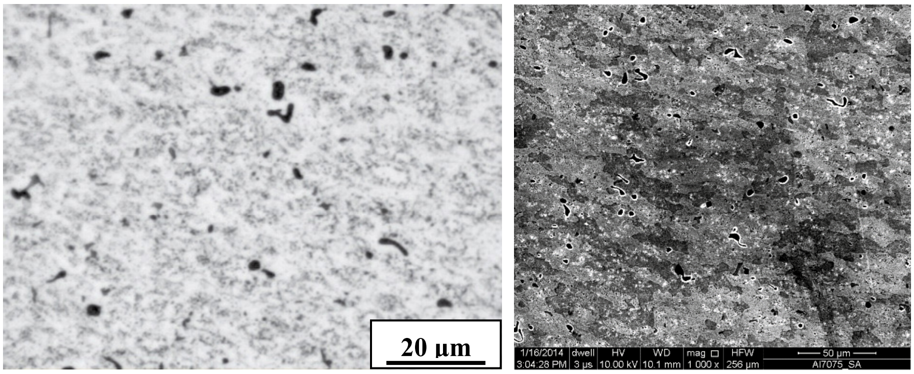

Fig. 1. (a) Optical and (b) SEM micrograph of AA7075.

3.2. Effect of Ultrasonic Shot Peening

3.2.1 Microstructure

Fig. 2 shows X-ray diffraction profile of the un-USSPed and USSPed AA7075. It is obvious that there was no phase transformation due to USSP. However, the diffraction peaks of the USSPed sample are apparently broadened and indicate surface grain refinement and increase in atomic level lattice strains. The average grain size of the USSPed 60 samples was calculated from diffraction line broadening of five Bragg reflection peaks of fcc-Al: (111), (200), (220), (311) and (222), using the Scherrer and Wilson equation and was found to be 20 nm. The internal microstrain developed due to micro-distortion of the lattice was calculated using Williamson Hull equation [Williamson et al. (1953)] and it was found to be 0.307%.

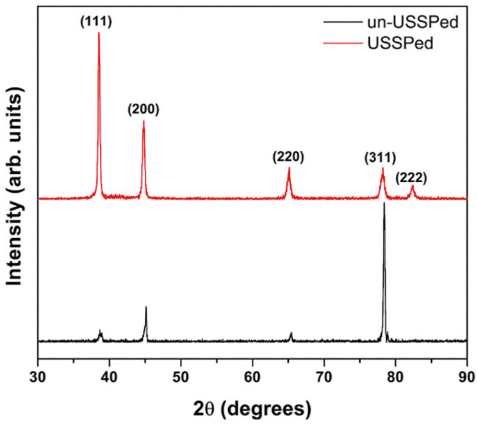

Fig. 2. XRD profiles of AA7075 in un-USSPed and USSPed 60 condition.

Fig 3(a) shows bright field TEM micrographs of the un-USSPed AA7075. The precipitates and the intermetallic particles may be seen distributed homogeneously throughout the grains. These intermetallic precipitates may be Al_3Fe and Al_7Cu_2Fe as reported earlier [Li et al. (2008) and Birbilis et al. (2005)]. Fig. 3 (c) shows bright field TEM micrograph of the sample USSPed for 60 seconds close to surface and its corresponding SAD pattern. The corresponding SAD pattern (Fig 3 d) shows elongated spots with discrete ring pattern, indicating formation of nanograins in the USSPed region with random orientations. The subdivision of subgrains to nanograins occurs due to high strain and strain rates in the surface region resulting from USSP. These nanograins were of approximately 20-30 nm size, which is consistent with the crystallite size calculated from XRD. There was also formation of large number of dislocation tangles which ultimately resulted in refinement of the microstructure in near surface region. The mechanism of grain refinement of materials with high stacking fault energy has been reported to be associated with deformation by dislocation slip. The observation of nanostructuring in the present investigation is in line with the proposed mechanism of formation of dislocation tangles in FCC system resulting at high strain rates near the surface region [Tao et al. (2002)].

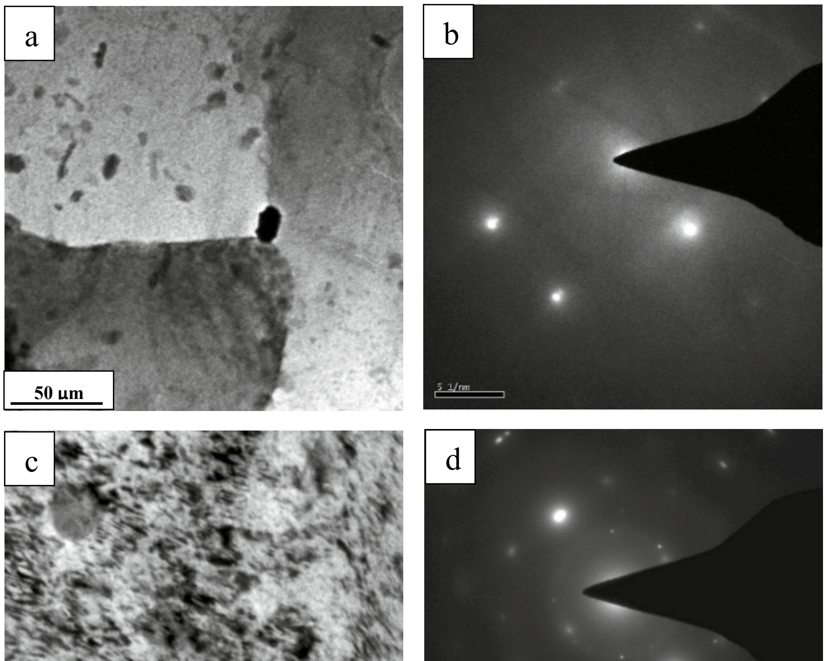

Fig. 3. TEM micrograph of alloy AA7075 (a) un-USSPed, (b) corresponding SAD pattern, (c) USSPed 60, (d) corresponding SAD pattern.

3.2.1 Low Cycle Fatigue Behavior

Fig. 4 shows variation of cyclic stress response with number of cycles at different total strain amplitudes, from ±0.40% to ±0.60%, at a strain rate of 5×10^{-3} s^{-1}, for the un-USSPed and USSPed 60 AA7075, at room temperature. The un-USSPed sample exhibited mild cyclic softening at strain amplitudes of ±0.50% and ±0.60%. Cyclic softening was more at the strain amplitude of ±0.50% as compared to that at ±0.60%. However, at the lowest strain amplitude of ±0.40%, there was initial hardening up to about 100 cycles, followed by nearly constant stress response.

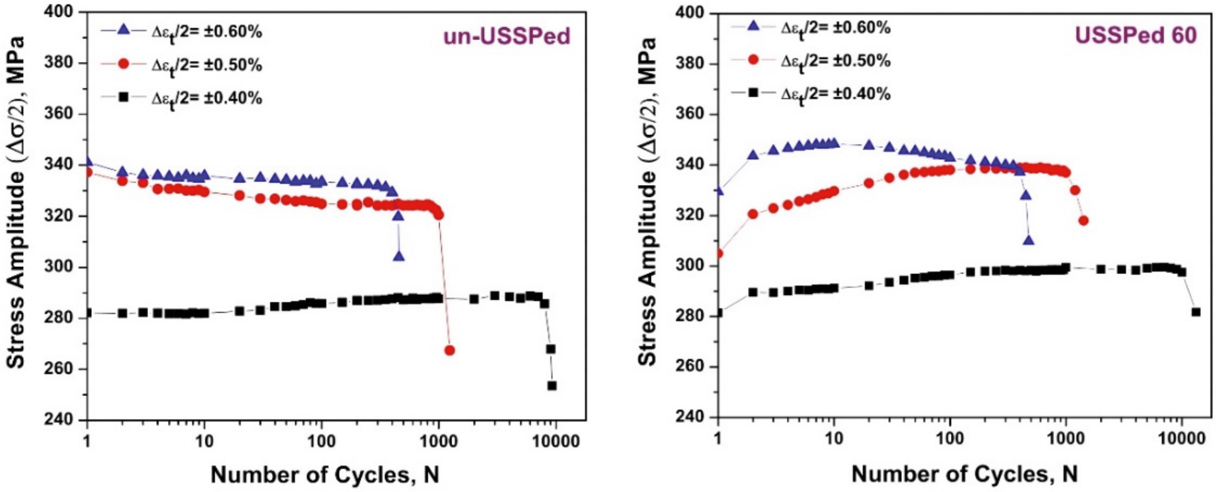

Fig. 4. Variation of cyclic stress response of the AA7075 in (a) un-USSPed, (b) USSPed 60 conditions.

In case of USSPed 60 samples, there was pronounced cyclic hardening in the beginning up to ~10 cycles, followed by softening till failure for the strain amplitude of ±0.6%. At the lower and intermediate strain amplitudes of ±0.4% and ±0.5% respectively, there was continuous hardening till failure. Irrespective of strain amplitude, there was initial cyclic hardening (upto ~10 cycles) and the degree of cyclic hardening increased with increase in strain amplitude.

Fatigue life of the AA7075 in un-USSPed and USSPed conditions for different total strain amplitudes is shown in Table 2. The percentage improvement in LCF life from USSP treatment was found to increase with decrease in strain amplitude. The low cycle fatigue life was improved by 15%, and 43% for the samples tested at strain amplitudes of ± 0.50% and ± 0.40% respectively, with respect to un-USSPed sample. The increment in LCF life at low strain amplitude may be understood from increase in resistance against crack initiation resulting from USSP. The combined effect of nanostructured surface layer and the induced residual compressive stresses from USSP, resulted in improvement in fatigue life. Similar observation on LCF behavior due to USSP have been made previously for 2014 Al alloy [Pandey et al. (2015)].

Table 2. Low cycle fatigue life of aluminium alloy 7075 in different conditions.

Total strain amplitude, ($\Delta\varepsilon_t/2$)	Low cycle fatigue life, N_f (cycles)	
	un-USSPed	USSPed
± 0.60%	456	478
± 0.50%	1240	1420
± 0.40%	9279	13226

The dependence of fatigue life as reversals to failure ($2N_f$), on plastic strain amplitude ($\Delta\varepsilon_p/2$), was analyzed using the Coffin–Manson relationship $\Delta\varepsilon_p/2 = \varepsilon'_f (2N_f)^c$, where ε'_f and c are fatigue ductility coefficient and fatigue ductility exponent respectively (Fig. 5). Coffin-Manson relationship was obeyed in the both un-USSPed as well as USSPed 60 samples.

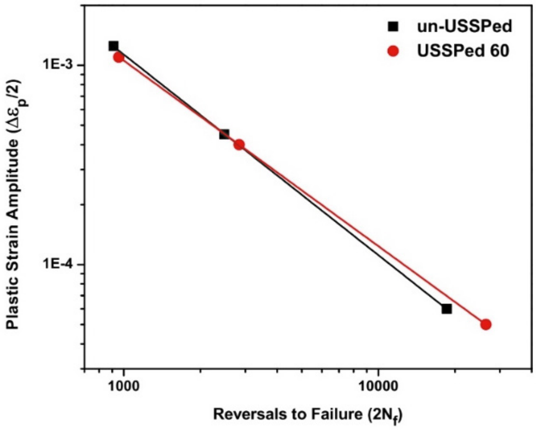

Fig. 5. Coffin-Manson plots of AA7075 in un-USSPed and USSPed conditions.

Effect of USSP duration on fatigue life at constant strain amplitude is shown in Fig. 6. In the un-USSPed condition the material exhibited initial softening, followed by mild hardening till failure while in the case of USSPed samples there was continuous hardening from first cycle to failure. The rate of cyclic hardening decreased with number of cycles in all the USSPed conditions. LCF life for different USSPed conditions at total strain amplitude of $\Delta\varepsilon t/2= \pm 0.4\%$ is shown in Fig. 7. There was little influence of USSP for 30 seconds on fatigue. However, increment in fatigue life of 54% was observed for the sample USSPed for 180 seconds followed by increment of 42% in that for 60 seconds. On the other hand, decrement in life was observed for the specimen USSPed for longer duration of 300 seconds as compared to the un-USSPed samples. Increase in fatigue life of the USSPed specimen was due to the combined effect of nanocrystallised surface layer and compressive residual stresses induced from USSP treatment. Nanocrystallized surface layer delayed the process of fatigue crack initiation whereas the subsurface compressive residual stresses slowed down the rate of crack propagation. Decrement in fatigue life of the sample USSPed for long duration of 300 seconds may be due to increase in surface roughness and formation of microcracks because of excessive work hardening from the longer USSP treatment. The decrease in fatigue life of the specimen USSPed for 30 seconds may be attributed relatively to more detrimental effect of increased surface roughness in comparison of the beneficial effect resulting from nanostructure and residual stresses.

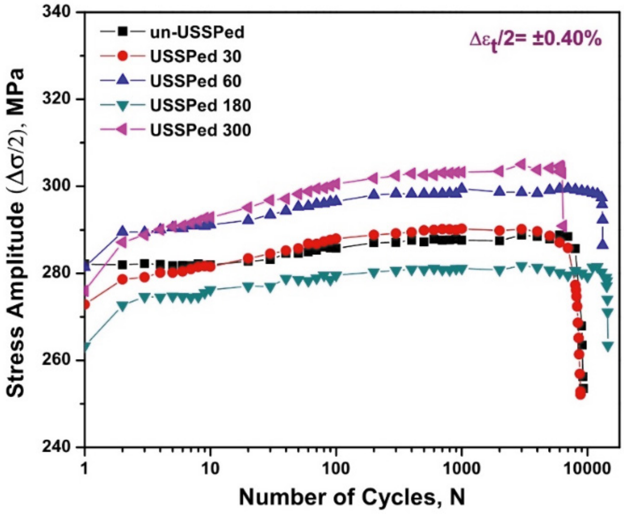

Fig. 6. Variation of cyclic stress response of the AA7075 in different USSP conditions at total strain amplitude of $\Delta\varepsilon_t/2= \pm 0.4\%$.

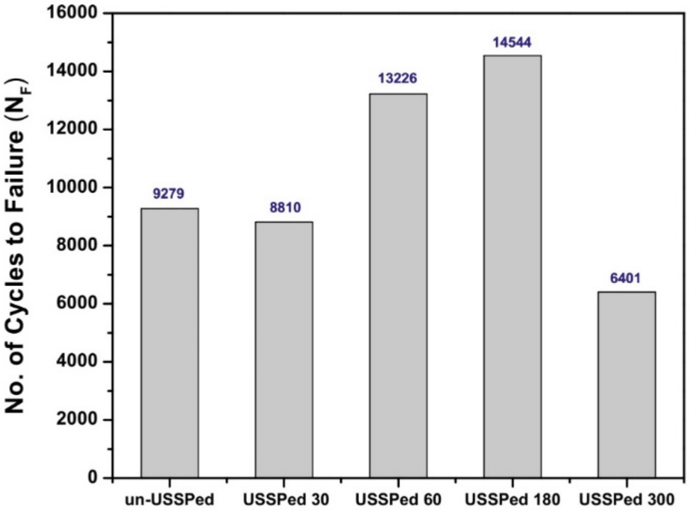

Fig. 7. LCF life for different USSPed conditions at total strain amplitude of $\Delta\varepsilon_t/2= \pm 0.4\%$.

The fractographs of the un-USSPed and USSPed 60 specimens, tested in fatigue at strain amplitudes of ± 0.5% and ± 0.6% are shown in Fig. 8. Characteristic fatigue striations were observed in all the conditions. Some voids may also be seen resulting from the shearing/cracking of the coarse precipitates during cyclic loading. The number of crack initiation sites was found to be more in the USSPed samples and it may be due to increase in surface roughness which acted as active site for crack nucleation due to stress concentration. However, most of these cracks did not propagate due to associated compressive stresses and thus leads to increase in LCF life.

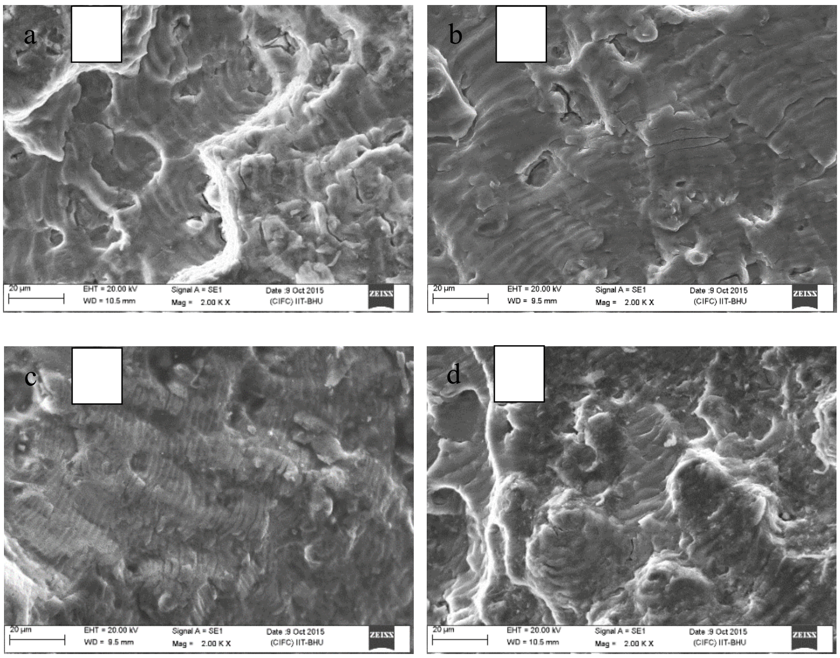

Fig. 8. Fractographs of AA7075 of the specimens tested in different conditions (a) un-USSPed at strain amplitude ± 0.6%, (b) USSPed at strain amplitude ± 0.6%, (c) un-USSPed at strain amplitude ± 0.5%, (d) USSPed at strain amplitude ± 0.5%.

4. Conclusions

Using USSP, a nanostructured surface layer was produced in AA7075 alloy and its effect on low cycle fatigue behavior was investigated. The following conclusions may be drawn from this study:

i. There was no phase transformation due to USSP and a nanostructured surface layer with an average crystallite size of 20 nm was developed.

ii. Significant increase in LCF life was observed due to USSP for 180 seconds. The effect of USSP was more prominent at lower strain amplitudes.

iii. The enhancement in LCF life was due to combined effect of surface nanostructure and the induced compressive residual stresses resulting from USSP treatment.

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