Effect of stress relieving treatment on low cycle fatigue behavior of USSP treated 7075 aluminium alloy

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Abstract. The effect of ultrasonic shot peening (USSP) on low cycle fatigue (LCF) behavior of the 7075 aluminium alloy was studied at room temperature. There was grain refinement approximately to 20 nm size, appreciable increase in micro hardness, and induction of residual compressive stress in the surface region, due to the USSP treatment. The modified microstructure in surface region of the specimens subjected to USSP was characterized by X-ray diffraction and transmission electron microscopy. There was marked increase in LCF life of the specimens due to USSP, however, LCF life of the USSP specimens was reduced due to subsequent treatment of stress relieving. The results are discussed in terms of the process of crack initiation and propagation in the different conditions.

1. Introduction
Precipitation-hardening 7075 aluminum alloys are used in aerospace applications due to good combinations of their specific strength, corrosion resistance and formability [1]. In these structural applications, the components undergo cyclic loading. Since nearly 90% failures of such components occur due to fatigue it is important to improve their fatigue resistance.

Fatigue cracks are known to initiate mostly from surface of the components, therefore there is much scope of surface modification in improving fatigue resistance of such components. Introduction of compressive residual stress in surface region of components through shot peening is a well-established process of surface treatment for improving fatigue life [2-4]. Ultrasonic shot peening (USSP) is a novel process of surface modification. It introduces compressive residual stress along with grain refinement in the surface region to nano level. As compared to conventional shot peening, USSP leads to development of higher compressive residual stress to a larger depth and better surface finish due to usage of steel balls of smoother surface. There have been several reports on the effect of USSP on microstructural modifications of various metallic materials like Al [5], Cu [6], stainless steels [7-8] and Ti [9], however, there are very limited data related to effect of USSP treatment on their low cycle fatigue (LCF) behavior.

In USSP, the specimen is bombarded with hard steel balls, causing plastic deformation in the surface region. The work hardening in the surface region leads to increase in micro hardness and development of high compressive residual stress. 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 [10-12]. The advantage of gradient structures lies in maximizing physical and mechanical properties and minimizing the material cost. The materials with gradient structure are fundamentally different from their conventional coarse-grained counterparts,
possessing high strength and hardness and enhanced physical properties. Therefore, it is expected that a structure with fine grain surface region and coarse grained interior should possess superior fatigue properties.

In the present investigation, we studied the effect of grain refinement in surface region combined with induced compressive residual stress, on LCF properties of the 7075 aluminium alloy and also the effect of relieving the associated residual compressive stress of the USSP specimens, without altering the nanostructure in the surface region, on the LCF behavior.

2. Experimental
The 7075 aluminium alloy 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 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

| Element | Zn | Mg | Cu | Si | Fe | Mn | Al |
|---------|----|----|----|----|----|----|----|
| Wt %    | 4.89 | 2.12 | 1.52 | 0.33 | 0.007 | 0.09 | Bal. |

Ultrasonic shot peening treatment of the alloy was performed with steel balls of 3mm diameter at an amplitude of 80µm for 180 seconds. Stress relieving treatment of the USSPed samples was done at 90°C for 4h, followed by furnace cooling. The specimen without USSP is designated as un-USSP, treated by USSP as USSP, and stress relieved after USSP as USSP+SR. A Rigaku X-ray diffractometer with Cu Kα radiation was used to determine phase constitution, average crystallite size and mean micro strain of the USSP specimen. Crystallographic structure of the USSP samples was characterized by XRD in 2Θ range of 30° to 90°. Residual stress analysis was also carried out using PANanalytical X-ray diffractometer. Microhardness was measured using Shimadzu micro-hardness tester. Electrochemical polishing of TEM foil was done in an electrolyte containing 20% nitric acid in methanol at -28°C at applied voltage of 20V. Transmission electron microscopy was done using TECNAI 20 G2 operating at 200 kV. LCF tests were conducted on a servo hydraulic MTS™ of 50kN (model 810) under total strain control mode.

3. Results and Discussion

3.1. X-ray Diffraction Analysis
X-ray diffraction profiles of the un-USSP, USSP and USSP+SR samples are shown in Fig. 1 (a). Peaks of only α-Al were observed for all the conditions. Thus, it was obvious that there was no phase transformation, neither due to USSP nor from the stress relieving treatment. Fig.1(b) shows diffraction peak corresponding to (220) for the USSP condition, broadening and shifting of peak to the side of lower angle is quite evident. Broadening was due to increase in lattice strain and refinement of surface grains.

![Figure 1. (a)](image1.png)
XRD profiles of un-USSP, USSP and USSP+SR samples and (b) (220) peaks of the base α-matrix.
The average grain size was calculated using Scherrer and Wilson equation [13] from the five diffraction peaks and was found to be 18nm and 20nm for the USSP and USSP+SR conditions respectively. The micro strain resulting from the USSP treatment was calculated using the Williamson Hull equation [14] and was found to be 0.320% and 0.285% for the USSP and USSP+SR conditions respectively. Substantial decrease in micro strain was due to stress relieving treatment and it is obvious from Fig. 1 (b) that after stress relieving the peak again shifts towards the higher angle side which may be attributed to decrease in micro strain and the peak is still broad due to presence of nano grains in the surface region.

3.2. Microstructural Characterization

Fig 2 (a) shows bright field TEM micrographs of 7075 aluminium alloy in the un-USSP condition. Fine precipitates with some coarse intermetallic particles are distributed homogeneously throughout the grains with some η (MgZn2) precipitates segregated at the grain boundary. The coarse intermetallic precipitates have been identified as Al3Fe and Al7Cu2Fe [15-16].

![Figure 2 TEM micrographs of the 7075 aluminium alloy: (a) un-USSPed, (b) corresponding SAD pattern, (c) USSP, (d) corresponding SAD pattern.](image)

Fig. 2 (c) shows bright field TEM micrograph of the USSP treated sample and its corresponding SAD pattern. Nano grains of approximately 20-30nm size are formed in surface region of the USSP specimen. Some of the grain boundaries are visible but many of them are not seen clearly. The formation of ring in the corresponding SAD pattern with some discretion indicates formation of nanograins in the USSP region with random orientations. The high strain and strain rates from USSP in the surface region led to subdivision of original coarse grains to nanograins. High density of dislocation network and dislocation tangles may be seen inside the grains, likewise the contrast within the grains is not uniform and indicates high level of internal stresses and elastic distortion in the crystal lattice.

3.3. Microhardness & Residual Stress variation

The microhardness in surface regions of the un-USSP, USSP and USSP+SR samples was measured. The hardness of the un-USSP sample was 154HV and was increased to 172HV after the USSP
treatment due to severe plastic deformation caused by repeated multiple impacts of hard steel balls and the consequent work hardening in the surface region. The increase in dislocation density and formation of nanograins increased the hardness in surface region. After the stress relieving treatment, the hardness was reduced to 157HV and was comparable to that of the un USSP specimen.

The residual stresses resulting from USSP treatment were found compressive in nature in surface regions of the USSP and USSP+SR samples. For the USSP treated specimen the residual stress was -261 MPa and was reduced to -111 MPa following the stress relieving treatment. It may be attributed to decrease in dislocation density for the USSP+SR sample that caused decrement in the compressive residual stress in the surface region. The main aim was to relieve the associated residual stress to bring out the effect of only the nanostructured surface layer on low cycle fatigue behavior of the 7075 aluminium alloy.

3.4. Low Cycle Fatigue Behavior
The variation of cyclic stress with number of cycles for the un-USSP, USSP and USSP+SR conditions at different strain amplitudes is shown in Fig. 3. LCF tests were conducted at three different total strain amplitudes of ±0.6%, ±0.45% and ±0.38% at a strain rate of 5 X 10^{-3} s^{-1}. It may be seen that there was continuous cyclic softening in the un-USSP specimen tested at the highest strain amplitude of ±0.60% till failure, whereas cyclic hardening was observed for the two lower strain amplitudes. In the case of USSP and USSP+SR conditions, cyclic hardening was observed at all the three strain amplitudes. Irrespective of strain amplitude, there was rapid cyclic hardening in the initial 10 cycles. The degree of cyclic hardening increased with increase in strain amplitude for the USSP samples. The initial rapid hardening was mainly from the work hardened surface layer and interaction of dislocations generated during cyclic loading, with the initial dislocations resulting from USSP treatment. The degree of cyclic hardening was more in the USSP+SR condition as compared to that in the USSP.

The dependence of fatigue life as reversals to failure (2Nf), on plastic strain amplitude (Δε_p/2), was analyzed using the Coffin–Manson relationship $\Delta \varepsilon_p/2 = \varepsilon'f(2N_f)^c$, where $\varepsilon'$ and c are fatigue ductility coefficient and fatigue ductility exponent respectively (Fig. 4). A linear trend in the variation may be observed for the un-USSP, USSP and USSP+SR conditions.

![Figure 3](image_url) Variation of cyclic stress in (a) un-USSP, (b) USSP and (c) USSP+SR conditions.
LCF life was found to increase for the USSP treatment and the increment in life increased with decrease in strain amplitude. The increment in fatigue life was due to combined effect of nanostructured surface layer and the induced compressive residual stresses from the USSP treatment [17]. The nanostructured surface layer resisted the initiation of fatigue crack whereas the compressive residual stress reduced the rate of fatigue crack propagation and led to increase in LCF life. After the stress relieving treatment LCF life was lower as compared to that of the USSP condition but was still higher than that of un-USSP.

Due to the severity of deformation resulting from USSP treatment there was increase in surface hardness and formation of nanograins in the surface region. The deformation was relatively more homogeneous in the USSP treated surface layer whereas it was heterogeneous in the un-USSP condition and concentrated along slip bands in coarse grains. The homogeneity of deformation decreased the degree of stress concentration hence the process of crack initiation was delayed. The surface and sub-surface compressive residual stresses reduced the tensile component of stress responsible for crack growth, thus the rate of crack propagation was reduced and fatigue life was increased. Thus, the nanostructured surface in combination with high compressive residual stress led to increase in fatigue life. In the case of USSP+SR samples only the nanostructured surface layer was there to delay the process of crack initiation and the fatigue life was higher than that of the un-USSP condition. However, due to absence of high compressive residual stress in the surface region there was no effect on the process of fatigue crack propagation and LCF life was less than that of the USSP condition.

4. Conclusions
i. A nanostructured layer with grain size of ~20nm was formed close to surface of the 7075 aluminium alloy subjected to ultrasonic shot peening.
ii. There was no phase transformation in the alloy due to the USSP treatment.
iii. The nanostructured surface layer associated with compressive residual stress led to enhancement of LCF life.
iv. Stress relieving treatment of the USSP specimens caused decrement in LCF life.
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