Mechanism of shot peening enhancement for the fatigue performance of AA7050

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Introduction

Shot peening has long been an industrial standard for airframe material, predominantly Al alloys. With an ever-present goal to increase efficiency, the aerospace community has continued to employ lightweighting strategies, which often translates to thinner components. The fatigue benefit of shot peening is often a compromise between the induced compressive residual stress field and the surface and near sub-surface damage. For thinner components, those with a greater ratio of surface area to volume, additional investigation is warranted to understand this mechanism of fatigue enhancement and associated engineering trade-offs. Sharp and Clark investigated the effect of peening on the fatigue life of 7050 aluminum alloy, with the intention of 'establishing a life-improvement-factor' [1] for components subjected to shot peening for structural use on the F/A-18 Hornet aircraft, of the Royal Australian Air Force. Particular concern in their work was the increased sensitivity of airframe structure and the subsequent fatigue life from surface features such as corrosion and mechanical damage [1] which could be imposed during the shot peening process. 7050 aluminum will most often be used in a condition with significant intermetallic precipitation; these precipitates impart the strength to the alloy but also are more brittle than the surrounding metallic matrix and hence could fracture during the shot peening process. In unpeened material these intermetallic particles, specifically Al_7Cu_2Fe, Mg_2Si, and Al_2CuMg, were the primary sites for crack initiation [2].

Objectives

The intention of this study was to better understand the microstructural effects of shot peening through a number of different experimental techniques. With experimentation and analysis centered on a comparison between an as manufactured aerospace grade aluminum alloy, AA7050-T7451, and shot peened samples of the identical material, the difference in material behavior and structural changes as a result of the shot peening process was identified. In this research, microstructural grain characterization and comparison of the as manufactured and shot peened AA7050-T7451 was carried out using a scanning electron microscope (SEM) in combination with electron back scatter diffraction (EBSD) to analyze grain sizes and orientations. This enabled the grain orientation, sizing, and shape to be used for statistical comparison. In order to carry out elemental analysis of constituent elements of the material, including secondary phase identification, energy dispersive spectroscopy (EDS) was employed. The intention of this practice is to positively identify precipitate particles, in order to carry out specific analysis and experimentation through nano-indentation hardness testing, and SEM imaging.

Methodology

The material utilized throughout this study is an aerospace grade aluminum alloy, AA7050. The material is tempered in the T7451 condition and produced in plate form. AA7050 is an Al-Zn-Mg-Cu-Zr alloy, which exhibits a combination of high strength and a high resistance to stress corrosion cracking. From a plate of the material AA7050-T7451, a set of 20 dog bone samples were machined from a rolled plate in the L-T direction. The samples have a nominal thickness of 1.6mm, a 3mm thick gauge section, and a length of 48mm; the basic shape was adapted from standard ASTM E8, but scaled to fit within the SEM used for the material characterization.

The shot peening processes was performed by Progressive Surface (Grand Rapids MI). Samples were shot peened on all faces, in a staged peening process involving fixing the samples onto a flat backing whilst the opposite side was peened. The peening media utilized for shot was a Z150 ceramic zirconia. The shot particle size ranges from 100-210 μm diameter. The shot was pressure blasted through a 5/16” V-type nozzle at a pressure of 6 PSIG, with a 45° angle of impingement from the horizontal surface, and a 6” standoff distance. One side was peened, the sample was flipped, and then the other side peened with the same processing conditions.

Electron microscopy was carried out using a FEI XL40 SEM with an EBSD system from EDAX Corporation. Because the surface of the as-machined fatigue specimens and the shot peened surfaces were too rough to collect accurate EBSD data, and the expected depth of maximum residual stress was on the order of 200-300 μm, the samples were polished to removed 90 μm from each surface using a 50 nm colloidal silica suspension. This surface, approaching a mirror-like surface, was then the surface characterized for structure as well as the final surface used for fatigue testing. Fatigue testing was performed in an MTS load frame at 3 Hz, with a stress oscillation between 20 to 400 MPa (this is approximately 85% of the yield stress for the material in this heat treatment condition). X-ray diffraction was used to determine residual stresses by using the $\sin^2\psi$ technique in a Phillips X’Pert2 diffractometer. Nanoindentation measurements were carried out with a Hysitron TI 950 sytsem and a Berkovich tip.

Results and analysis

Based on optical profilometry using a Zegage 3D Profiler, the baseline sample displayed a peak to valley surface roughness of ~2 μm, whereas the shot peened sampled has a range of ~10 μm. The surface after shot peening and subsequent increments of polishing using colloidal silica are shown in a series of optical micrographs in two minute increments in Figure 1. EBSD of polished samples (Figure 2) showed no statistically significant grain size change between samples subjected to shot peening and those in the as machined state once 90 μm of material were removed.

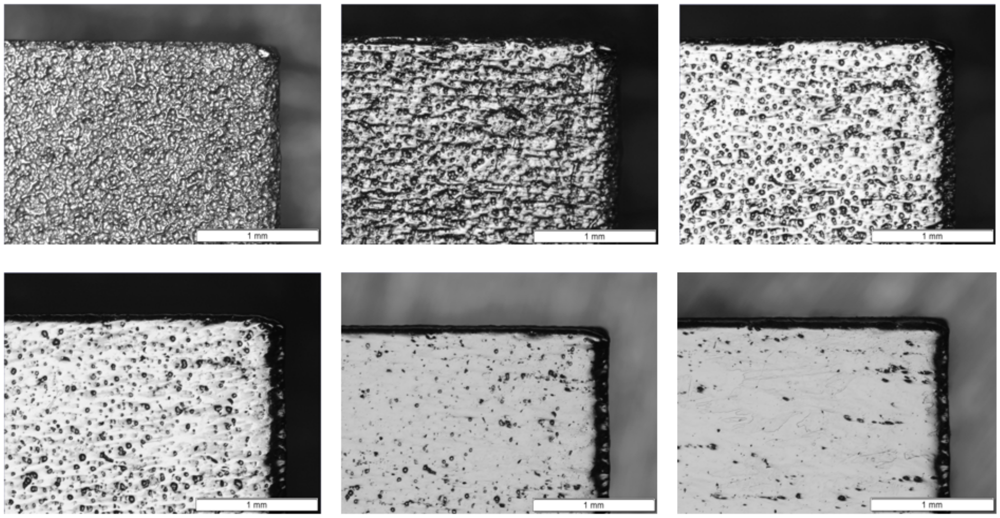

Figure 1. Incremental polishing of a shot peened sample of AA7050-T7451, demonstrating depth of surface roughness. Scale bar is 1 mm.

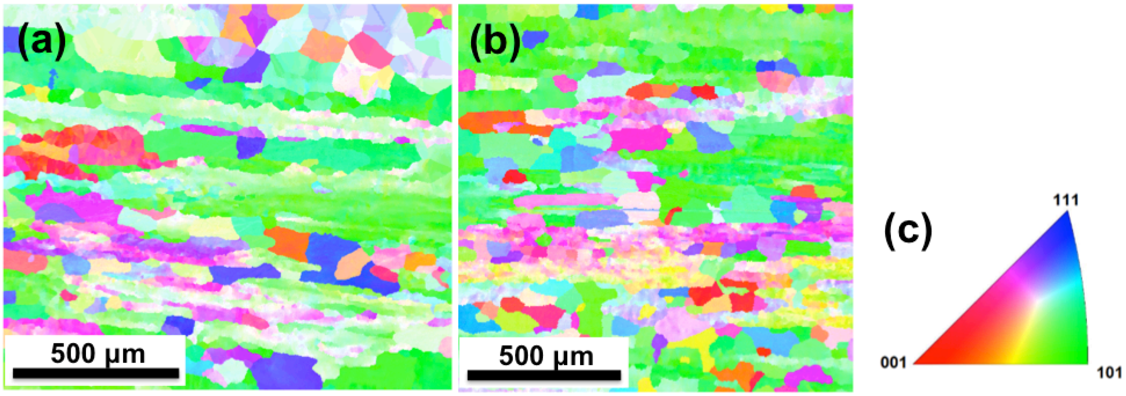

Figure 2. Inverse pole figure maps to demonstrate the microstructure of (a) the baseline sample and (b) the shot peened sample. The stereographic triangle depicting orientation is shown in (c).

Interrupted fatigue testing showed that the compressive stress on the surface of the shot peened sample did relax after approximately 15,000 cycles (see Figure 3). The electron microscopy of Al_7Cu_2Fe precipitates in samples before and after fatigue testing (these are the samples which have been polished after shot peening and after the initial machining processes, in most cases these are at 90 µm removed but in one case the sample was polished 400 µm during the testing portion of the characterization) is shown in Figure 4. The important feature to note is that in the case of the shot peened sample even with some evidence of debonding at the intermetallic precipitate there is no evidence of cracking in the metallic matrix.

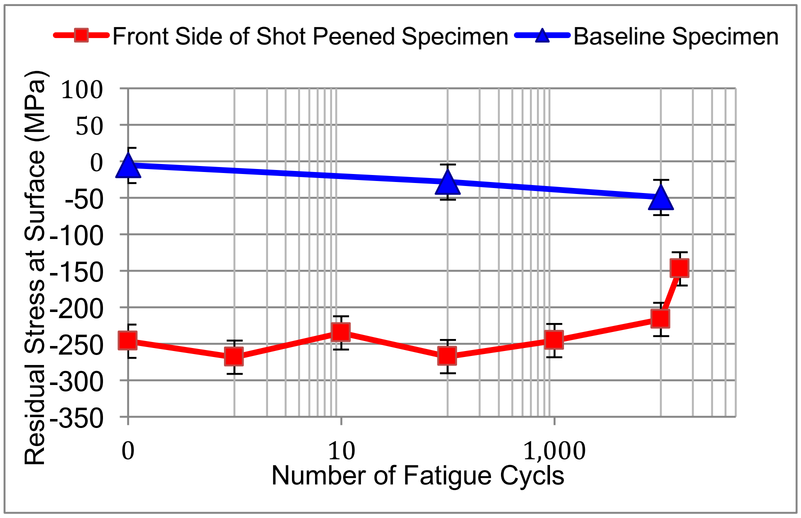

Figure 3. Residual stress as a function of fatigue cycles showing stress relaxation occurring at approximately 15,000 cycles.

Nanoindentation of the intermetallic particles in the as manufactured and shot peened condition was carried out using a Hysitron Triboindenter. The nanoindentation process allows a determination of the elastic modulus in a lateral area on the order of 1 µm. This size was chosen to be small enough to be solely within an individual particle, but large enough to minimize the noise caused by nanoscale surface roughness due to cracking. Figure 5 shows the perceived modulus for the precipitates as heat treated, as shot peened, and after fatigue testing of the non-shot peened sample. Cracks in the precipitate will lead to a more compliant measurement (i.e. a lower perceived modulus); the shot peened sample exhibits a quantifiable increase in compliance.

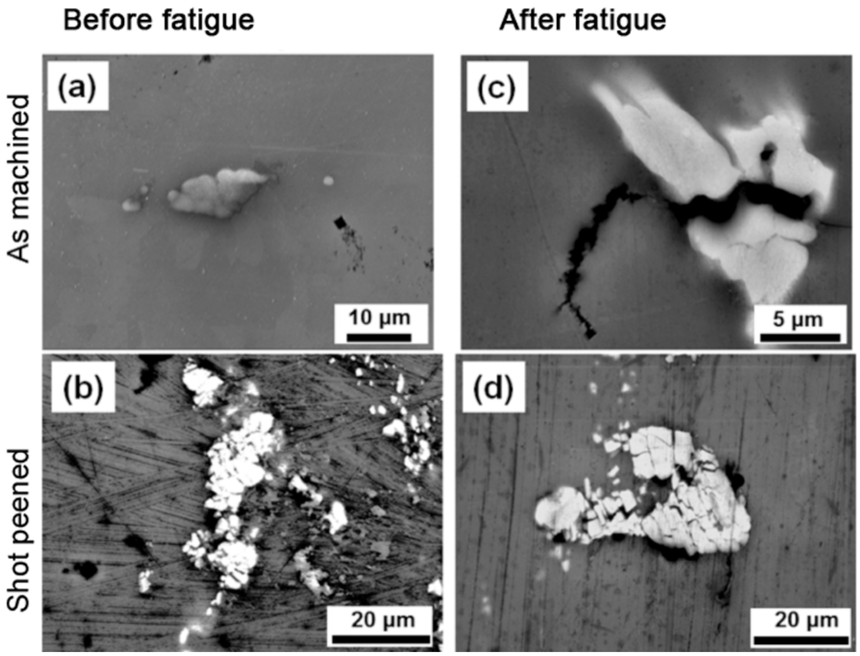

Figure 4. Precipitate microstructure imaging using SEM showing (a) an intact precipitate (400 µm subsurface) before fatigue, (b) a cracked precipitate (90 µm subsurface) in the shot peened sample before fatigue (c) a cracked precipitate demonstrating incubation and propagation into the material matrix following 5500 fatigue cycles (d) a cracked precipitate (100 µm subsurface) following fatigue at 4500 cycles with evidence of de-bonding but no cracking observed in the material matrix.

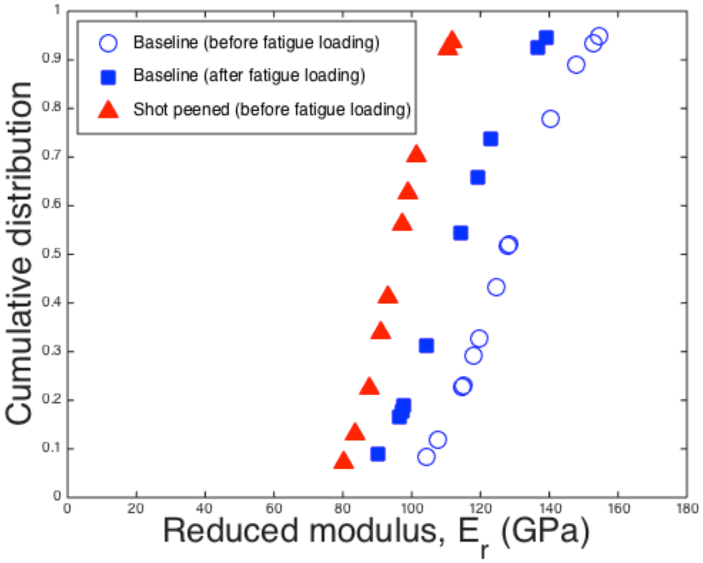

Figure 5. Perceived elastic modulus of Al_7Cu_2Fe precipitates in a variety of conditions. Cumulative distribution plots shown to identify the range of values, lower modulus values are indicative of cracked intermetallic particles.

Conclusions

Surface topography following shot peening has been measured, and while shot peening alters the roughness of Al 7050, there is no evidence of a discernable difference in microstructure between shot peened and baseline samples in terms of grain size at a sub-peening depth of approximately 90 μm. The crucial results from this work are that subsurface Al_7Cu_2Fe precipitates in the shot peened samples do fracture from the shot peening process prior to fatigue loading. However, there is no evidence that the cracked particles propagate any cracks during fatigue; the residual stress imparted from shot peening restricts any crack growth during fatigue loading for the conditions used in this study.

References

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