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ADP013491

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EFFECTS OF SHOT PEENING PROCESSING ON THE FATIGUE BEHAVIOR OF THREE ALUMINUM ALLOYS AND TI-AL-4V

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Abstract: The fatigue strength of three shot-peened aluminum alloys (Al 7075-T651, Al 2024-T351 and Al 2014-T6) and a titanium alloy (Ti-6Al-4V) was measured to determine the differences in shot peening quality from three vendors that were given the same shot peening parameters. Shot peening produces surface roughness, a cold-worked layer and, most importantly, a residual stress layer that resists the propagation of fatigue cracks. Significant vendor-to-vendor differences in fatigue properties were found, with Vendor 1 giving the greatest fatigue lifetimes.

Key Words: Aluminum; fatigue; notched; residual stress; shot peening; titanium

Introduction: Fatigue behavior of metals is greatly influenced by the condition of the surface. Very smooth surfaces tend to show more resistance to fatigue than those that are rough. When there are compressive residual stresses at the surface, the fatigue strength is greatly improved. Over the past 50 years, shot peening has been used to improve the fatigue properties of a variety of metals, especially those that are used in aircraft applications. Shot peening is a mechanical surface treatment that introduces a roughened surface, a compressive surface layer, and increased dislocation density (cold work) near the surface. During shot peening, particles, typically steel or glass beads, are impacted onto a surface imparting significant deformation. Typically, the compressive layer improves the resistance to crack propagation, and thereby increases fatigue lifetime. In some instances where crack nucleation controls fatigue behavior, the increased surface roughness from shot peening is a detriment to fatigue strength.

The purpose of this investigation is to compare the fatigue properties of a Ti-6Al-4V alloy and three aluminum alloys that had been shot peened by three different vendors. The same shot peening specifications were given to the three vendors, one primary and two second source. Therefore, the differences in shot peening quality were assessed based on fatigue behavior.

Experimental: Three heat-treated aluminum alloys, Al 7075-T651, Al 2024-T351 and Al 2014-T6, were tested, along with a Ti-6Al-4V alloy that was in a solution treated and overaged (STOA) condition. For the Ti-6Al-4V alloy, an equiaxed grain structure was observed, as shown in Figure 1, that consisted of α and transformed β in an acicular structure. The α grain size was ~ 7.5 μm. Notched circular fatigue specimens were fabricated from the heat-treated alloys by Metal Samples of Munford, Al. They were 3" long with a gage length of 1" and a gage diameter of 0.315". The notch was centered in the gage length with a notched diameter of 0.255" and a notched radius of curvature of 0.024". The stress concentration factor k_t of the notch was calculated to be 2.4.

The machined specimens were shot peened with steel shot by three vendors (Vendor 1, Vendor 2 and Vendor 3). Specimens were shot peened over the gage and notched areas (also, the threaded portion for the Ti specimens) using specification MIL-S-13165C and the following parameters: Al (intensity- 0.006 – 0.010 N, shot size- S110, 100% coverage), and Ti (intensity- 0.005 – 0.011 N, shot size- S70 and 200% coverage).

Fatigue tests were conducted in pulsating tension using an Instron 1350 servohydraulic testing machine with an 8500 series control module. There were 11 specimens shot-peened by each vendor for the Ti alloy, while only 6 specimens from each vendor for each of the three Al alloys. The actual notched diameter for each specimen was used in determining the cross-sectional area for the Ti specimens, while the nominal diameter was used for the Al specimens. All tests were conducted at a frequency of 25 Hz and with a minimum load that was 10% of the maximum load, or R = 0.1. To determine the stresses for high-cycle fatigue and the endurance limit for the Ti specimens, many tests were arrested at 1,500,000 cycles and the fatigue specimen was retested at a higher stress level. This testing procedure is similar to the staircase test method [1] used for fatigue testing with a limited number of specimens.

Results and Discussion: S-N fatigue curves for the titanium alloy of stress vs. number of cycles-to-failure (CTF) were generated and are shown in Figures 2, 3, 4, for Vendors 1, 2 and 3, respectfully. It should be noted that the stress plotted is the applied stress σ_a not the maximum stress (k_t x σ_a) due to stress concentration at the notch. All three S-N curves are similar in shape and have a narrow stress region where there was failure by high-cycle fatigue. At this stress level, there is a large amount of scatter in the fatigue data. For example with Vendor 2, one test conducted at 72 ksi gave a fatigue life of 7.5 M cycles, while another gave 130,000 cycles at 72.5 ksi. But for each vendor, there was a different stress level where high-cycle fatigue and run-outs were observed, and this stress level was considered to be the endurance limit. For Vendor 1, the endurance limit was approximately 76 ksi, while it was ~ 74 ksi for Vendor 3 and ~ 72 ksi for Vendor 2.

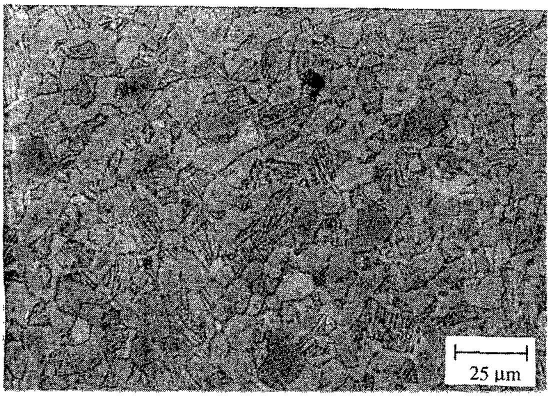

Figure 1 Microstructure of the heat-treated titanium alloy consisting of α and transformed β in an acicular structure, with an α grain size of ~ 7.5 μm. (500 X)

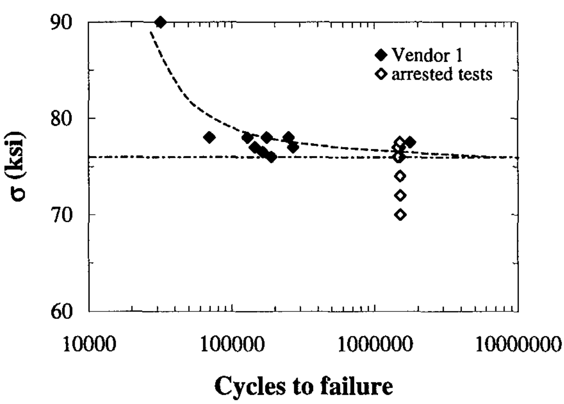

Figure 2 S-N curve for specimens shot peened by Vendor 1 with an endurance limit of ~ 76 ksi.

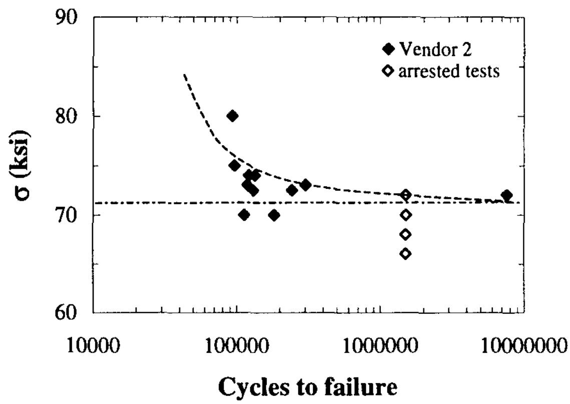

Figure 3 S-N curve for specimens shot peened by Vendor 2 with an endurance limit of ~ 72 ksi.

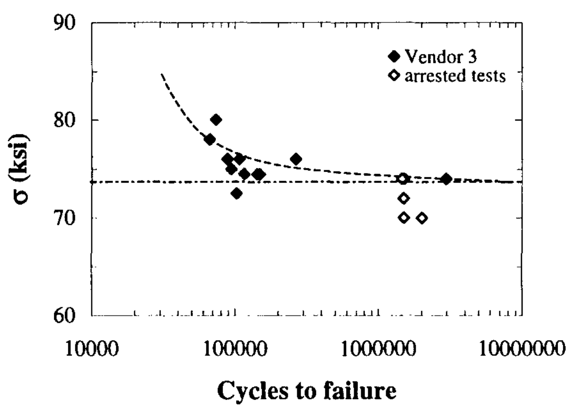

Figure 4 S-N curve for specimens shot peened by Vendor 3 with an endurance limit of ~ 74 ksi.

For the three aluminum alloys, there was less data for each S-N curve and the fatigue limit was harder to discern. Therefore, the vendor differences in fatigue behavior are easier to observe by comparing and ranking the data, as shown in Table I. Vendor 2 consistently had lowest fatigue lifetimes at several different stress levels compared to Vendors 1 and Vendor 3. This trend is clearly seen with all three alloys. Even with the data for all three alloys, the difference between Vendors 1 and 3 is rather small with Vendor 1 showing slightly longer fatigue lifetimes. With only six test specimens tested per condition, this number may be insufficient for measuring the smaller difference between Vendors 1 and 3.

Table I Vendor rank for fatigue lifetime at a given stress level for each aluminum alloy

Stress, σ (ksi)	Al 2024-T351	Al 7075-T651	Al 2014-T6
35	$V_2 \sim V_1 \sim V_3$	only V_1 tested	$V_2 \sim V_3 < V_1$
32.5	$V_2 < V_1 \sim V_3$	$V_2 < V_1 \sim V_3$	not measured
31.25	not measured	V_1 runout	not measured
30	only arrested tests	$V_2 < V_1 \sim V_3$	$V_2 < V_3 < V_1$
27, 27.5	not measured	only V_2 tested	$V_2 < V_3$

Since the specimens were fabricated, heat treated and tested in the same fashion, the difference in the fatigue behavior should be the due to differences in shot peening from each of the three vendors. Shot peening affects the surface of a metal by three mechanisms: (1) introduces surface roughness, (2) imparts cold work (higher dislocation density) and (3) forms a compressive residual stress layer. Gerdes and Luetjering [2] studied the effects of shot peening on notched Ti-6Al-4V specimens with several different microstructures. They found that the fatigue strength was determined by the compressive residual stresses retarding the crack propagation rate. Other authors [3,4] have also found that the compressive stress layer formed during peening has the most significant impact on fatigue lifetime for several other titanium alloys. Sridhar *et al.* [5] found through X-ray analysis that the compressive surface layer was approximately 0.4 – 0.7 μm deep, depending on the alloy and shot peening parameters. Similar compressive surface layer thicknesses were found in Al 2024-T3. [6] When the compressive stresses were relieved during thermal annealing [2,3], the fatigue properties were severely degraded, thereby showing the importance of the compressive layer formed during shot peening.

Surface roughness and cold work may also play a role in the observed differences in fatigue behavior. Since the surface roughness has not been measured, differences in this parameter for each vendor may be important. The nucleation of cracks is influenced by the surface roughness and it can be an important factor when crack nucleation is the dominant mechanism controlling fatigue behavior. However, crack propagation rates through the compressive layer usually control the fatigue lifetime, since there are always local stress concentration sites that quickly nucleate cracks. [7] As for cold work, Leverant *et al.* [3] found that cold work in their studies of a Ti-6Al-4V alloy, with a similar microstructure to the current study, had very little influence on the crack growth rate and fatigue strength.

Microhardness measurements were made in an attempt to detect differences in the compressive layer and in the amount of cold work after shot peening. They were made on cross sections perpendicular to the loading direction using a Wilson Series 200 testing machine with a Vickers indenter. Measurements were taken in the center and approximately 50 μm from the surface, along with several hardness profiles. Wagner and Mueller [6] found increased dislocation densities in a 400 μm deep surface layer for Al 2024-T3. Hardness measurements for the current investigation were typically in the 305 – 325 HV range for Ti-6Al-4V and 170 – 185 HV for Al 7075-T651. In Figure 5, two depth profiles taken on a Ti specimen showed very little change in hardness from the surface to a depth of approximately 1.5 mm. For several other Ti and Al specimens, there was very little difference in microhardness measurements taken at the center of the specimen to those ~ 50 μm from the surface. In studies on fatigue behavior of shot peened titanium, Berger and Gregory [8] found that shot peening does not increase the microhardness readings substantially in the near-surface layer for a β-titanium alloy However, Rios *et al.* [7] did find significant differences in microhardness with depth below the surface for Al 2024-T351. They also developed a model that incorporates shot peening to predict fatigue lifetimes.

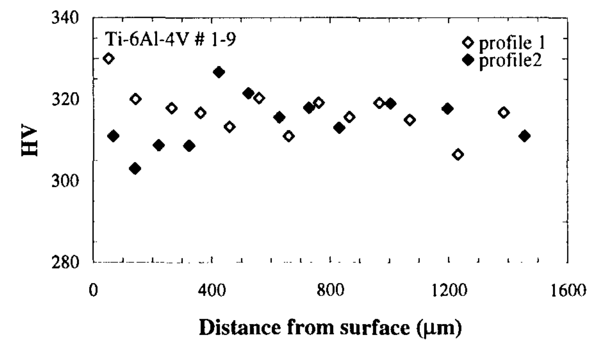

Figure 5 Vickers microhardness profiles on a Ti-6Al-4V specimen.

Conclusions: Differences in fatigue properties were observed for both Ti-6Al-4V and the three aluminum alloys that were shot peened by three different vendors. For the titanium alloy, Vendor 1 had the highest endurance limit at ~ 76 ksi, while Vendor 2 had the lowest at ~ 72 ksi and Vendor 3 was ~ 74 ksi. For the aluminum alloys, fatigue lifetimes of the vendors were similarly ranked. The differences in fatigue behavior are likely due to differences in the compressive residual stress layer formed during shot peening, which retarded the crack propagation rate.

Acknowledgement: The author would like to express appreciation to George Liu and Dr. Kirit Bhansali of the Aviation Missile Command (AMCOM) for support for this project.

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