Influence of shot peening process variations on the fatigue life of Al-Cu-Li alloys

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Introduction

Al-Cu-Li alloys, also known as third generation Al-Li alloys, have drawn attention for use in aerospace due to their combination of high strength, toughness, density reduction and corrosion resistance. The reduction in the lithium content to levels such that copper is the primary alloying addition induces microstructural changes that resolve some of the problems encountered with the second generation of Al-Li alloys. Along with good performance properties, aerospace applications require long service lifetimes which typically involves surface anodization for corrosion resistance and primer adhesion along with shot peening for fatigue life enhancement for aluminum structures.

Al-Cu-Li alloys are used in the peak aged –T8 temper whereas most conventional Al-Cu alloys are used in the naturally aged –T3 or –T4 tempers. While the peak aged temper provides a number of performance benefits, it reduces the fatigue life of the alloy [1-3].

One of the most effective techniques for extending fatigue life is to induce compressive residual stress at the part surface. [2] The superposition of compressive residual stresses onto the in-service stress profile induced by part loading has the effect of locally reducing the maximum stress and the portion of the stress cycle spent in tension. This affects both crack initiation and fatigue crack growth rate. Shot peening provides compressive residual stresses and also introduces cold working at the surface, both of which are beneficial for improving high cycle fatigue life [3]. However, shot peening also roughens the surface texture which can be detrimental to fatigue life [4] [5].

The anodize process introduces pits onto the aluminum surface, and these pits are frequently the source of fatigue crack initiation [6 7]. Pits or other surface stress concentrations can shorten the time required to initiate cracks. Glass bead peening has been successfully applied to overcome the fatigue life deficit caused by chemical milling [8]. Corrosion fatigue studies have also demonstrated that shot peening can improve the fatigue life for samples with surface pits [9].

In addition to changes in peening media, other shot peen parameters such as velocity, impact angle or peening time can be used to modify the combination of compressive residual stress and surface roughness imparted by the peening operation. This has been optimized for conventional alloys, but in order to explore the shot peening surface modification imparted to an Al-Cu-Li alloy, process variations induced by changes in peening media and intensity were screened to determine their impact on high cycle fatigue life.

Objectives

The objective of this research was to determine whether conventional peening process media and intensities as used for Al-Cu-Mg alloys in the naturally aged tempers are suitable for peening of peak aged Al-Cu-Li alloys.

Methodology

Material

AW231, a developmental Al-3.3Cu-0.9Li-0.6Mg-0.2Ag plate material produced by Constellium was used in this study. The plate was 30 mm thick in the peak aged –T84 temper. The typical tensile strength for this heat lot of the alloy is 512 MPa.

High cycle fatigue life (greater than 10^5 cycles) is based on the combination of crack initiation and crack propagation to final failure. To examine the effect of peening process variations on fatigue life, two types of peening media were used. The first was CW-32 conventional steel shot produced from conditioned cut wire. The second was Z150 ceramic media produced by the Saint-Gobain Group and sold under the trade name of Zirshot®.

Test specimens

Flat test specimens 6.35 mm thick were machined from the centerline of the plate stock. The specimen geometry incorporated a notch that introduced a stress concentration factor of 1.5. All edges in the test section were machined to produce a nominal radius of 0.8 mm to avoid edge roll-over during the shot peening operation. Peening operations were conducted using an air nozzle machine with a duration required to produce visual coverage of 100 percent.

Experimental procedure

The Al-Cu-Li specimens were subjected to different peening conditions as shown in Table 1. Five replicate specimens were used for each condition.

Table 1: Peening conditions

Code	Condition	Media	Peening Intensity
AM	As-machined	N/A	N/A
SP	Conventional shot peen	Steel CW-32	0.127mm A
CP	Ceramic media peen	Zirshot Z150	0.102mm N
DP	Duplex Conventional + Ceramic media peen	Steel CW32 + Zirshot Z150	0.127mm A 0.102mm N

After peening, all specimens were chemically cleaned with an alkaline cleaner to remove any residue, de-oxidized and boric acid-sulfuric acid anodized. Fatigue tests were conducted in laboratory air in accordance with ASTM E466 with a peak bulk section stress of 234 MPa and R=0.06.

To more completely understand the relationship between the peening process settings and high cycle fatigue life, the sample closest to the typical life of the specimen set was investigated to determine surface roughness and residual stress. Surface roughness was investigated with a Bruker Contour GT-K1 3D Optical Microscope. Residual stress profiles were determined by the hole drilling method in accordance with ASTM E837 using a Vishay Micro-Measurements RS-200 Milling Guide. Two residual stress profiles were obtained for each specimen.

Results and analysis

Fatigue test results

All fatigue specimens fractured in the test section near the narrowest portion of the notch (highest K_t). Fatigue test results are shown in Figure 1.

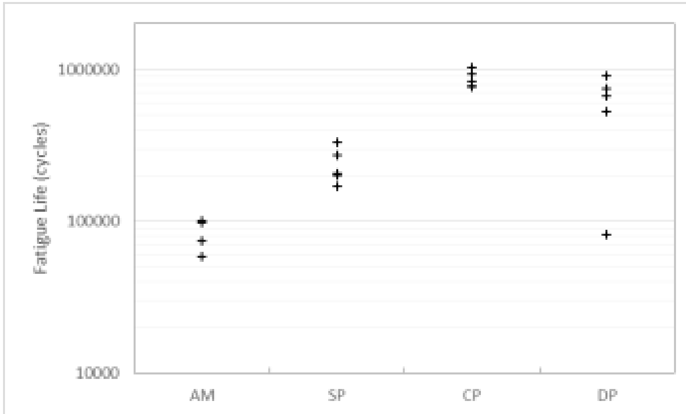

Figure 1: Fatigue life of peened Al-Cu-Li specimens

For assessing the effect of process variables on fatigue life, the geometric mean fatigue life was used to represent the typical life for each set of replicates. Changes in peening media clearly impacts fatigue life. With the exception of the dual peened condition, the amount of scatter in the results was low.

Residual stress results

Hole drilling residual stress measurements were taken from opposite sides of the fracture surface, in the full width portion of the test gauge. Only the normal stress components in the direction of the applied load were considered. Individual measurements are shown in Figure 2 images a) through d) with a solid line representing the average of the two measurements.

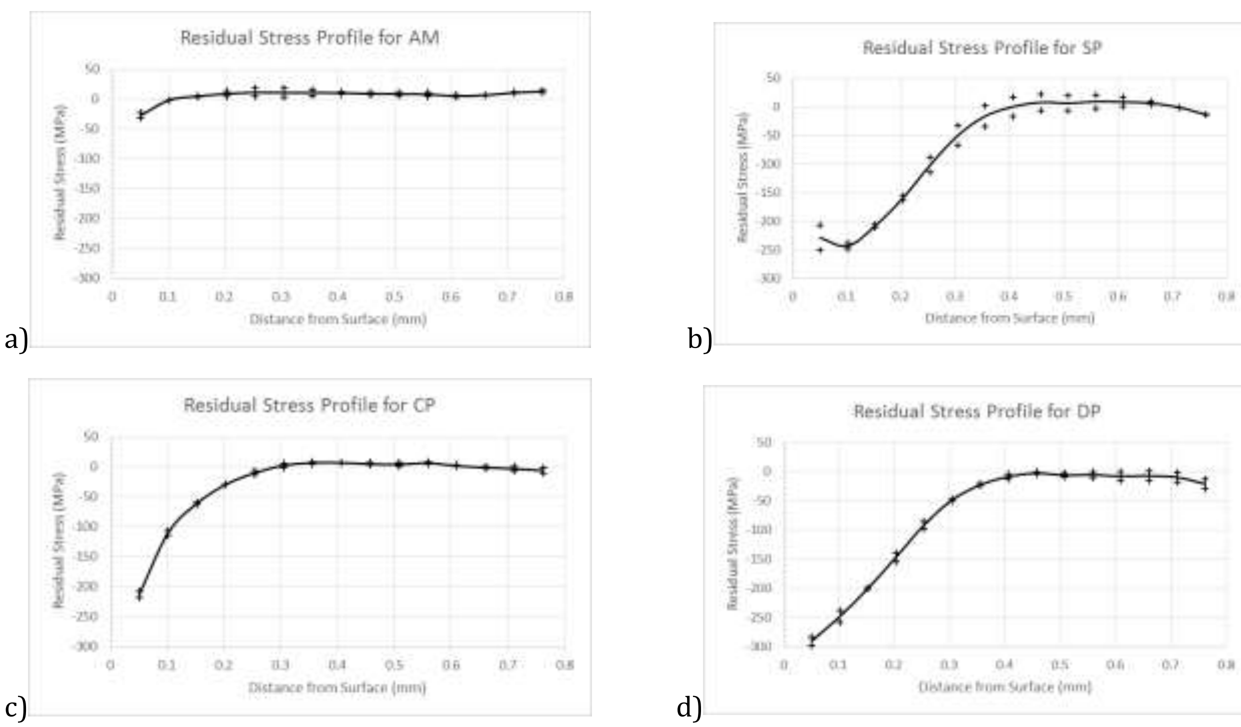

Figure 2: Residual stress profiles - a) As-Machined + anodized, b) Conventional steel media shot peened + anodized, c) Ceramic media shot peened + anodized, d) Duplex conventional steel media followed by ceramic media peened + anodized.

With the exception of the conventional steel media shot peened sample, the individual residual stress measurements at the same depth exhibited only minor differences (less than 20 MPa). The conventional shot peened sample exhibited a maximum difference of 44 MPa in the first measurement which equates to slightly less than 20% of the mean value at that location.

Roughness profile results

The Bruker system uses white light interferometry to capture an accurate 3D profile of the surface being examined. From this data, a variety of surface characterization measurements can be calculated such as roughness average (Ra), root mean square (Rrms), nominal profile to valley depth (Rv), nominal profile to peak height (Rp) or the distance between the highest peak and the lowest valley (Rt) [10]. These values are represented in Figure 3.

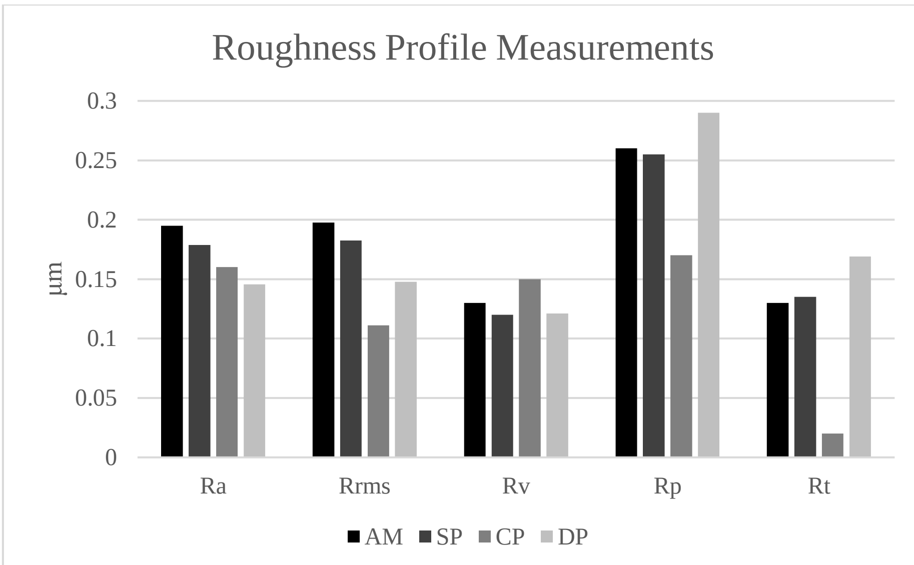

Figure 3: Surface roughness measurements for different peening conditions

Analysis of results

Surface modification via shot peening results in competing attributes – compressive residual stresses provide fatigue life enhancement while the peening action itself roughens the surface. Surface folds and other defects are a source for crack initiation. Overpeening can result in decreased fatigue performance when the negative impact from a roughened surface outweighs the compressive residual stress advantage. [11]

The surface roughness measurements showed a strong correlation to fatigue life. The relationship between root mean square roughness and the number of cycles to failure is shown in Figure 4.

Surface roughness is related to localized stress concentrations [12], and roughness has an impact on fatigue life. [13] Peak aged second generation Al-Li alloys showed reduced time to crack initiation in shot peened specimens [14], so it is reasonable to expect that local stress concentrations due to surface roughness will have an increased impact on the third generation Al-Li alloy tested in this experiment. A study on the effect of shot peening intensity on a conventional Al-Cu alloy, 2024, showed that residual stress increased with increasing peening intensity, but that fatigue life at the highest intensity was not improved due to increased surface roughness [15].

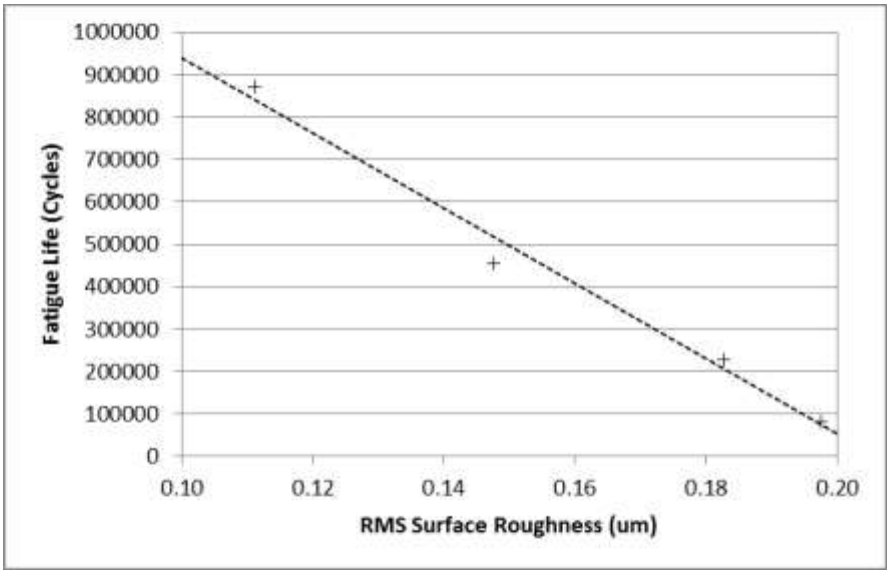

Figure 4: Fatigue life as a function of specimen surface roughness

a) b)

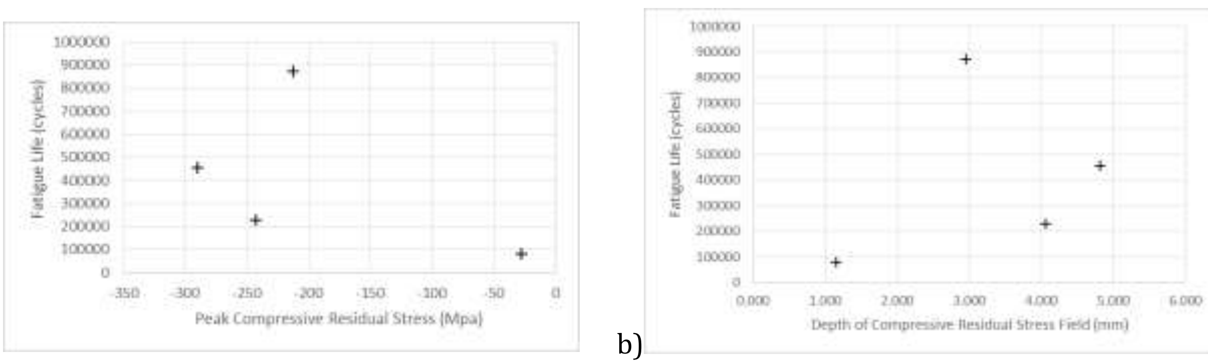

Figure 5: Fatigue life as a function of residual stress parameters – a) peak compressive residual stress, b) depth of compressive residual stress field

Two measures frequently used to determine the effectiveness of shot peening operations are the magnitude of the compressive residual stresses present and the depth of the compressive residual stress region. As seen in Figure 5, fatigue life did not correlate to these two measures.

Surface residual stress measurements were not captured in this study. Extrapolation of the first two residual stress measurements to the surface suggests that the lower intensity peening may produce a higher magnitude of compressive residual stress at the surface. In this study, all of the specimens were anodized prior to testing. Since the anodize process introduces small pits onto the surface and surface defects are also introduced by peening, high cycle fatigue life may be more susceptible to the resulting localized surface stress concentrations. A higher magnitude of compressive residual stress at the surface may be more effective in countering these effects than a greater compressive layer depth.

Conclusions

This study only examined a few media-induced variations in shot peening process parameters. As Al-Cu-Li alloys are introduced into aerospace, additional research to customize shot peening process settings for optimized fatigue life is warranted.

- Surface roughness has a strong influence on fatigue life of peened and anodized Al-Cu-Li alloys.
- Although the magnitude and depth of the compressive residual stress profile can be increased with conventional shot peening, the ceramic media peening resulted in a smoother surface finish and longer fatigue life.
- This study warrants additional research to further investigate shot peening process parameters on Al-Cu-Li alloys as they are introduced into the aerospace industry.

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