Effect of Coverage in Ball-Burnishing on Fatigue Performance of Al2024-T4

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Abstract

The effects of coverage in ball-burnishing (BB) on the surface and sub-surface layer properties such as roughness and residual stress profile as well as on HCF strength were evaluated in Al2024-T4. Results are compared with previous observations on coverage effects in shot peening (SP). While SP at low coverage was seen to drastically deteriorate high-cycle fatigue (HCF) performance relative to an electropolished reference (EP), no such detrimental effect of low coverage was observed in BB. These results are explained mainly by differences in the resistance to fatigue crack nucleation between these two conditions. SP is beneficial only when the early fatigue crack nucleations caused by the high local stress concentrations at indentations are overcompensated by the well developed residual compressive stresses (at higher coverage) and their beneficial effects on micro-crack retardation. However, the absence of these stress concentrations in BB reduces their detrimental effects on the fatigue performance at low coverage.

Keywords: Ball-burnishing, coverage, surface layer properties, fatigue performance

Introduction

Previous work has demonstrated that the fatigue performance of aluminum and titanium alloys can be markedly influenced by shot peening coverage [1-5]. It was shown that low coverage could lead to fatigue lives even lower than that in the untreated electropolished reference condition [2]. These results were explained by the compressive residual stresses being not fully developed at low coverage and, therefore, were not able to compensate the early fatigue crack nucleation caused by the high induced surface roughness. The fully developed residual compressive stresses in 100% coverage were then seen to drastically reduce micro-crack growth by which the early fatigue crack nucleation was much overcompensated leading to marked enhancements in the overall fatigue life. While some SP instructions in aircraft even recommend coverage in the excess of 100% (e.g., 400%), earlier work on Ti-6Al-4V [6] has indicated so-called over-peening effects, i.e., losses in fatigue life if coverage higher than 100% were used.

While the effect of BB on fatigue performance has also been studied for a number of materials including titanium, aluminium and magnesium alloys [8-10], there is lack of information on whether coverage in BB is as important as in SP.

Therefore, the present investigation was undertaken to study the effect of coverage in BB on the surface layer properties and the HCF performance.

Experimental methods

The age-hardenable aluminium alloy Al2024 was received as Ø 65 mm extrusion from Otto Fuchs Metallwerke in Meinerzhagen, Germany. Specimen blanks (10 x 10 x 60mm) were taken with the load axis parallel to the extrusion direction. These blanks were solution heat treated at 495 ºC for 1h followed by water quenching. All blanks were naturally aged for at least 5 days at room temperature resulting in condition T4. Tensile tests were done on threaded cylindrical specimens with a gage diameter of 6 mm using an initial strain rate of 10^{-3} s^{-1}.The resulting tensile properties were 380 MPa for yield stress, 555 MPa for ultimate tensile strength, 74 GPa for Young's modulus and 0.23 for true fracture strain.

Rotating beam specimens were machined having a cylindrical gage length and diameter of 20mm and 6mm, respectively. BB was applied using a conventional lathe and a burnishing tool from ECOROLL Company by which a hard metal ball of Ø 3mm (HG 3) was hydrostatically pressed onto the rotating specimen surface.

To achieve various coverage; two routes were applied;

- To apply lower coverage, the specimens were fed manually with the same rotational speed to keep a certain distance between the BB-passes (referred as M-coverage). This allows changing the M-coverage degree from 20% to 78% based on the step width between the BB-tracks.

  The coverage in this case was calculated based on the SP-coverage definition; in terms of the fraction of burnished-area to the total area.
- To achieve higher coverage, specimens were fed automatically with various rates (*f*) at a rotational speed of 150 rpm. This was referred as A (automatically fed). The coverage is then calculated from the formula [11, 12];

  $$C = \frac{b - f}{b} * 100\%$$

  where *b* is the width of a single BB-track as shown in Figure 1. Measurements were done by optical microscopy.

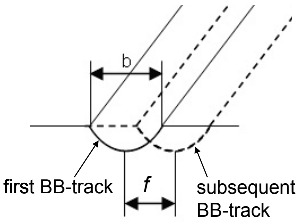


Figure 1: definition of BB-coverage parameters

After BB, the surface topography was characterized by roughness measurements using a profilometer from Perthen Company. Macroscopic residual stresses were determined through the incremental hole-drilling method by which an oscillating drill (Ø 1.9mm) is driven by an air-turbine providing a rotational speed of 200,000 rpm. From the back strains measured by strain gage rosettes, the residual stresses were calculated using linear elasticity concepts. The electrolytically polished condition (EP) was taken as the baseline (0% coverage) to which the various BB conditions will be compared.

Results and Discussion

The effect of burnishing pressure on the fatigue life at a stress amplitude of σ_a= 350 MPa after BB with A-coverage (IC-A 53%) is illustrated in Figure 2.

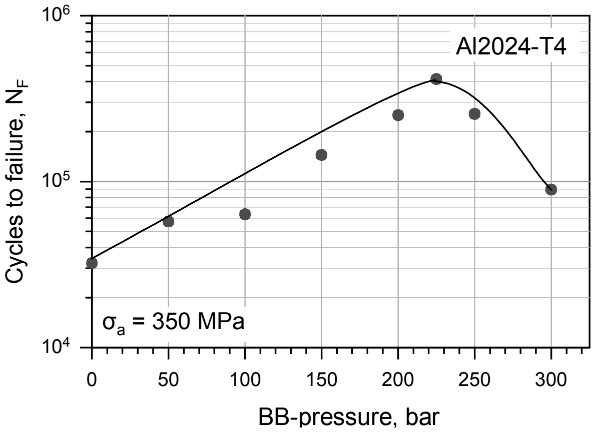
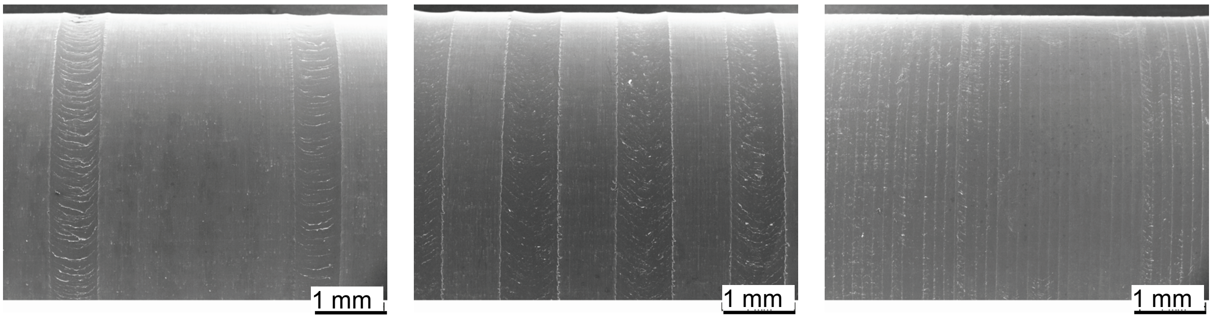


Figure 2: Fatigue life in Al2024-T4 vs. BB-pressure in IC-A (53%)

The fatigue life increases greatly with increasing BB-pressure up to 225bar. By further increasing the BB-pressure, the fatigue life drops again. Therefore, a BB-pressure of 225bar was chosen for studying the effect of coverage on fatigue performance.

Figure 3 illustrates the SEM surface topography after BB using various M-coverage ranging from low coverage LC-M = 20% (Fig. 2a) over intermediate coverage IC-M = 47% (Fig. 2b) to intermediate A-coverage IC-A = 53% (Fig. 2c).



a) LC-M (20%) b) IC-M (47%) c) IC-A (53%)

Figure 3: Surface topographies in Al2024 T4 (SEM): Effect of coverage

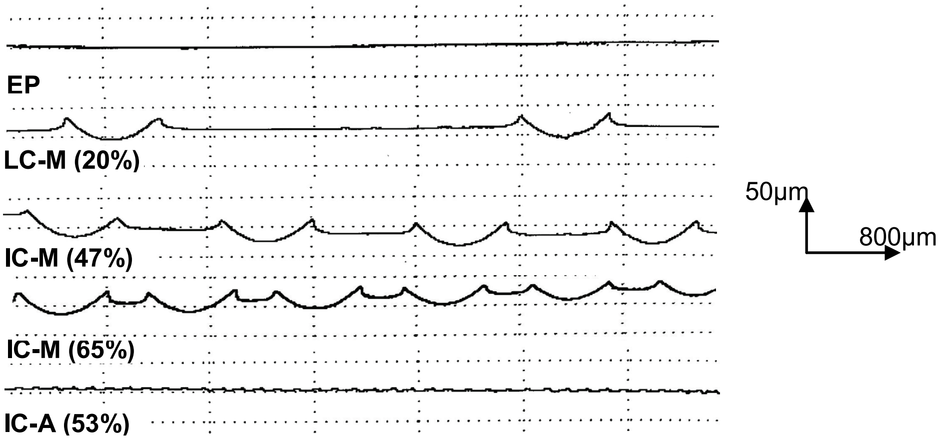


Figure 4: Surface roughness profiles of the various conditions (225bar BB-pressure)

The surface roughness profiles as measured by a profilometer clearly reflect the various degrees of coverage (Fig. 4). Starting with the very low roughness of EP, an increase in M-coverage from 20% to 65% clearly increases the frequency of occurrence of roughness tips and valleys. Because of the constant BB-pressure, the valley depth is also roughly constant amounting to about 20µm. However, the surface roughness profile of IC-A (53%) is much smoother approaching the very low roughness of the reference EP (Fig. 4).

The residual stress-depth distributions after BB are illustrated in Figure 5. Compared to LC-A 23%; FC-A (83%) results in markedly higher magnitude and deeper compressive residual stresses. This difference can be attributed to the overlapping of BB-tracks in FC.

In order to understand why no apparent difference between IC-M (20%) and LC-M (78%) was observed (Figure 6a), measurements on LC-M (20%) were repeated at another surface position (Fig. 6b) denoted as position 2 (Fig. 7b) while the result on LC-M (20%) in Figure 6a is denoted as position 1 (Fig. 7a). At position1, the hole was drilled directly onto a BB-track (Fig. 7a), at position 2, it was drilled in between 2 BB-tracks (Fig. 7b). As seen in Figure 8, there is a distinct difference in the residual stress-depth profiles measured from positions 1 and 2. Obviously, the compressive residual stresses clearly depend on the measured position indicating that the stress distribution of LC-M is quite inhomogeneous. Similar results are also reported on LC in SP [2].

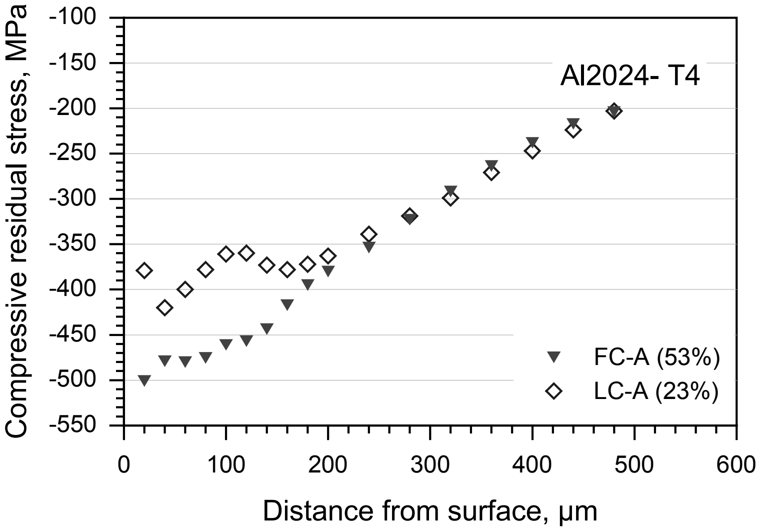
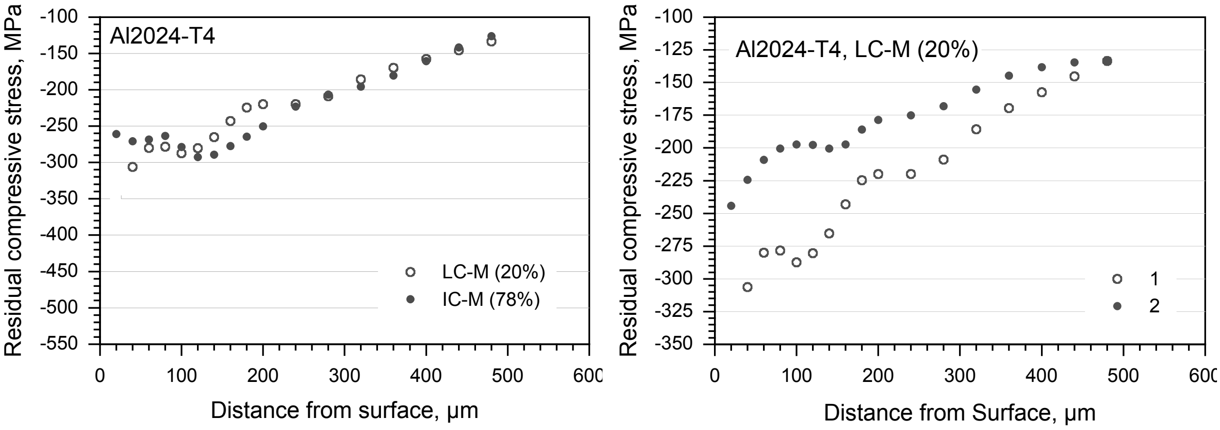
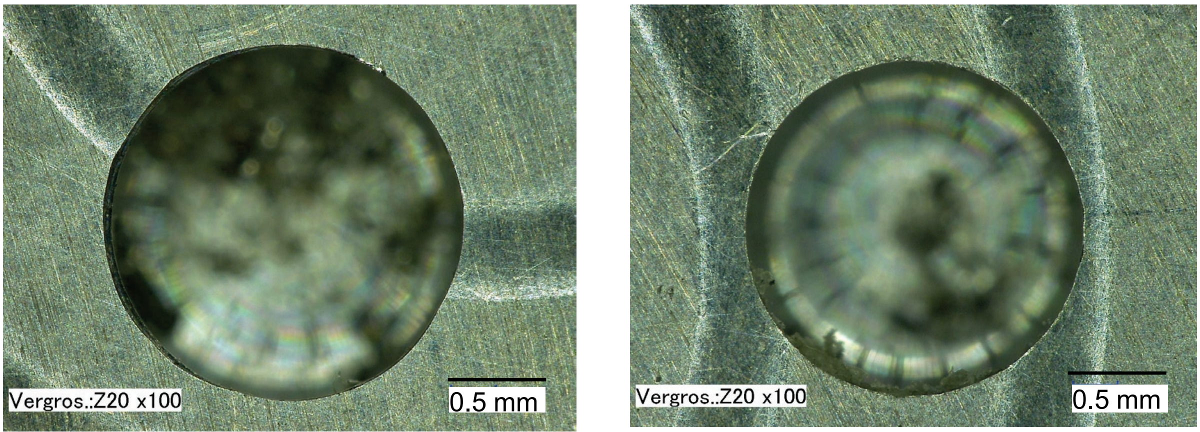


Figure 5: Residual stress-depth profiles for various coverage (225bar BB-pressure)



a) b)

Figure 6: Residual stress-depth profiles for manually BB-samples (225bar BB-pressure)



a) Position 1 b) Position 2

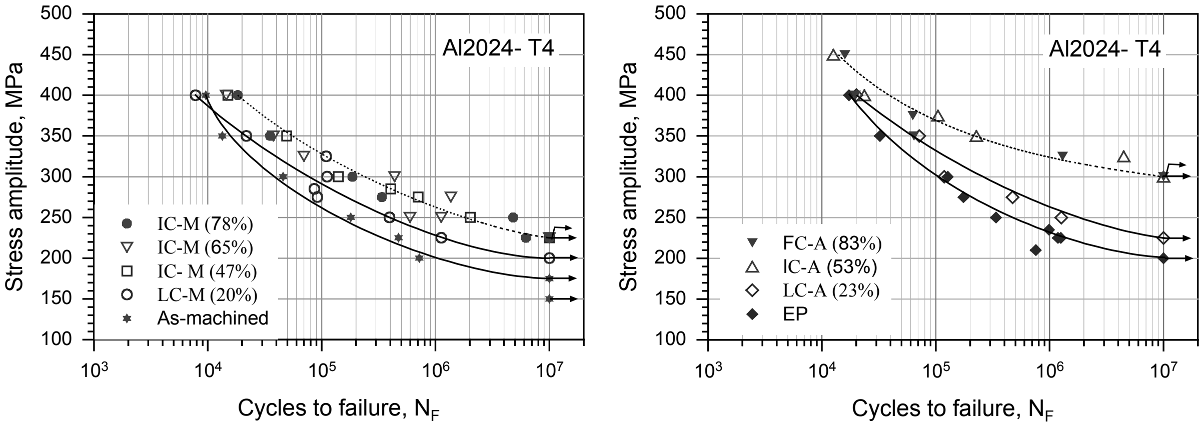
Figure 7: Two different positions of residual stress measurements in LC-M (20%)

The S-N curves for a range of coverage are shown in Figure 8. Compared to the as-machined conditions; the very low M-coverage (Fig. 8a) increase the fatigue strength from

175 MPa to 200 MPa. Further increase in the coverage from 47% over 65% to 78% results in a further enhancement in the fatigue life of the as-machined conditions and increasing the fatigue strength to 225 MPa, however there is no significant difference in the fatigue life by changing the coverage from 47% to 78% which could be attributed to the not fully developed compressive residual stresses.

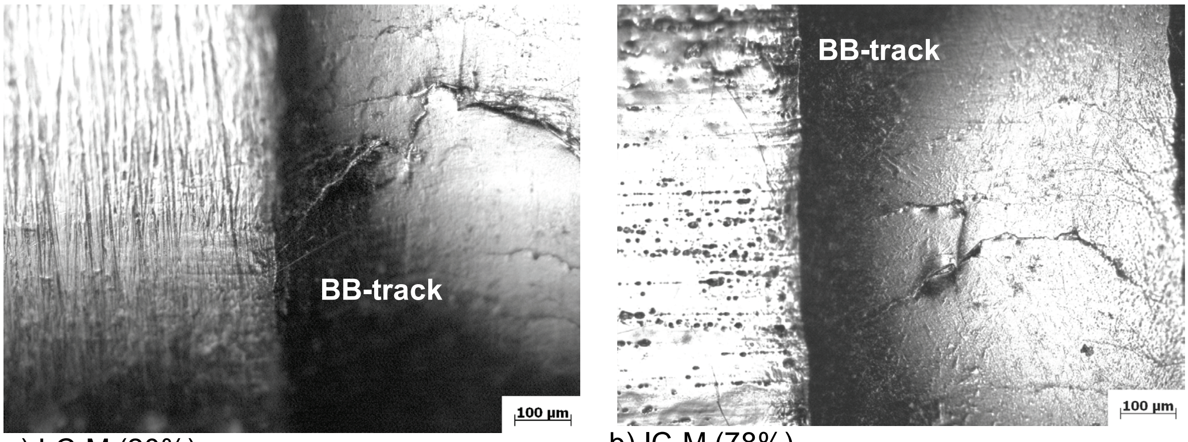
Applying various A-coverage leads to a marked improvement in the fatigue life compared to the EP reference condition (Fig. 8b). The lower coverage LC-A (23%) increases the fatigue life of the EP-reference conditions from 200 MPa to 225 MPa, however this result is comparable to the fatigue performance after applying higher M-coverage (compare Fig. 8a and Fig. 8b). The pronounced improvement in the fatigue life is obtained by applying intermediate coverage IC-A (53%) and full coverage FC-A (83%); however, there is no difference in fatigue life by changing the coverage from 53% to 83%.

Optical microscopy in Figure 9 reveals that in both LC-M and IC-M cases, fatigue cracks nucleate within single BB-traks and then propagate through un-burnished regions.



a) b)

Figure 8: S-N curves: Effect of coverage in BB (225bar BB-pressure)



a) LC-M (20%) b) IC-M (78%)

Figure 9: Fatigue crack nucleation at single BB-traks

These results are very similar to the results reported earlier on SP-LC and SP-IC [2]. Fatigue cracks were seen to nucleate early in their life at single indentations due to stress concentration in these areas. Residual compressive stresses in SP-LC and SP-IC were not fully developed and therefore, could not effectively decrease the growth rate of the micro-cracks.

Conclusions

Comparing the effect of coverage on HCF performance of Al2024-T4 between BB and SP, the following conclusion can be drawn:

1) Compared to SP-LC, BB-LC has less detrimental effect. This is explained by the fact that larger stress concentrations at single shot indentations in SP are pronounced than those produce in BB-tracks.
2) In the case of SP, the maximum roughness values are independent on coverage, while in the case of BB, the roughness in BB-FC decreases greatly compared to the values measured in BB-LC and BB-IC.
3) Fatigue performance in SP is micro-crack propagation controlled independent on coverage.
4) In contrast to SP, fatigue performance in BB changes from micro-crack propagation controlled (LC) to nucleation controlled (IC, FC) due to the drastic decrease in roughness. Therefore, there is a steep increase in fatigue life and fatigue strengtht as the full coverage reaches.

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