COVERAGE EFFECTS IN SHOT PEENING OF AL 2024-T4

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INTRODUCTION

It is often anticipated that 100% coverage in shot peening is required to achieve full benefit in terms of near-surface high dislocation densities, residual compressive stresses and fatigue performance [1]. Since the residual stress field caused by a single impact, however, is much greater than the size of the indentation, it can be argued that 100 % coverage may not be required [2]. On the other hand, there are shot peening specifications that require even more than 100 %, e.g., 200 % coverage. The present work was aimed at evaluating the effect of coverage in shot peening on the fatigue performance of the well known aircraft alloy Al 2024-T4. Particular emphasis was put on studying the effects of coverage on the resistances to fatigue crack nucleation and micro-crack growth.

EXPERIMENTAL

The age-hardening aluminum alloy Al 2024 was received as extrusion (Ø 63 mm) from Otto Fuchs Metallwerke in Meinerzhagen, Germany. Specimen blanks (10 x 10 x 50 mm) were taken with the long axis parallel to the extrusion direction. These blanks were solution heat treated at 495°C for 1 hour followed by water-quenching and naturally aged for at least 5 days at room temperature (condition T4).

Tensile tests were performed on threaded cylindrical specimens having gage lengths and gage diameters of 25 mm and 5 mm, respectively. The tensile properties ($10^{-3}\,s^{-1}$ initial strain rate) were as follows: Young's modulus E = 74 GPa, yield stress $\sigma_{0.2}$ = 415 MPa, tensile strength UTS = 595 MPa, tensile elongation El = 18.9 % and true fracture strain $\varepsilon_F = 0.23$.

Shot peening was done using a gravity induction system and spherically conditioned cut wire (SCCW14) having an average shot size of 0.36 mm. Small slits were applied in the shot feed system to reduce the mass flow to 45 g/min in order to enable low coverage peening at reasonable exposure times with sufficient reproducibility. The distance between nozzle and work piece surface was 60 mm.

The Almen intensity was measured on conventional A-type and N-type Almen test strips. In addition, strips of Al 2024-T4 having thicknesses of 1.3 mm and 2.0 mm were machined with the same dimensions in length and width as the Almen strips. These aluminum strips were taken to enable measurements of the degrees of coverage as well as deflections as a function of exposure time on the test material itself. Quantitative metallography (Image C analysis) was used to determine coverage degrees.

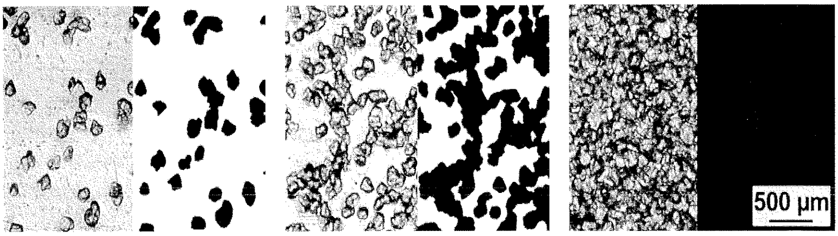
The surface roughness was measured by a profilometer.

Shot peening-induced residual stresses were evaluated with the incremental hole drilling technique using an oscillating drill with a 1.9 mm diameter driven by an air turbine with a rotational speed of about 200.000 rpm. The shot peening-induced strains in the surface layers were measured with strain gage rosettes at drilled depths of about every 10 µm. The residual stresses at each depth were then calculated from the measured strain gage response using the macroscopic Young's modulus of E = 74 GPa and a poisson's ratio of 0.30.

Fatigue tests were performed on hour-glass shaped specimens with a gage diameter of 3.6 mm in rotating beam loading (R = -1) in air at a frequency of 100 Hz. Before shot peening to various degrees of coverage, all specimens were electropolished. Roughly 100 µm were removed from the as-machined and mechanically pre-polished surface to ensure that any machining effect that could mask the results was absent. The electrolytically polished condition (**EP**) was also taken as the baseline (0% coverage) to which the shot peened conditions with various coverage degrees will be compared. To study fatigue crack nucleation and micro-crack growth, fatigue tests were interrupted after certain number of cycles and the surface of the specimens was studied using a specimen holder that enables defined specimen rotation under an optical microscope at 500x magnification.

RESULTS AND DISCUSSION

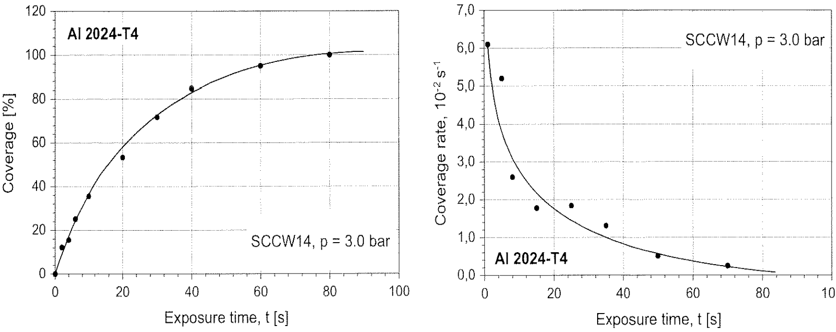
Coverage examples of shot peened Al 2024-T4 are illustrated in Fig. 1a-c. In each case, optical micrographs (left side) are shown together with image C converted pictures (right side).



a) **LC** (16 %) b) **IC** (53 %) c) **FC** (100 %)

Fig. 1: Examples of various degrees of coverage in Al 2024-T4

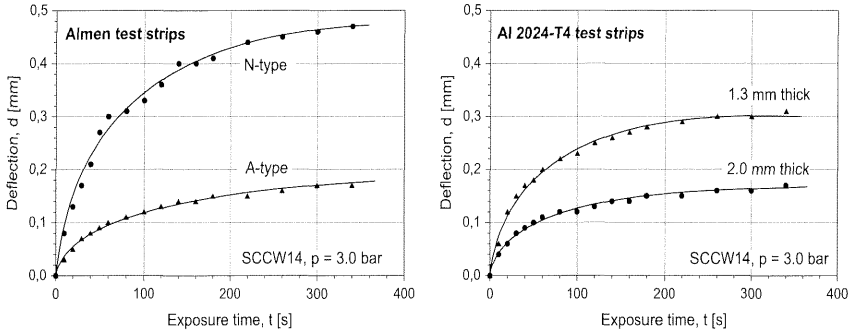
Peening with SCCW14 for exposure times of 4, 20 and 80 s resulted in coverage degrees of 16 % (low coverage, **LC**), 53 % (intermediate coverage, **IC**) and 100 % (full coverage, **FC**), respectively. The development of coverage with exposure time is shown in Fig. 2.



a) Coverage vs. exposure time b) Coverage rate vs. exposure time

Fig. 2: Development of coverage in shot peening of Al 2024-T4

The coverage first strongly increases with time and then gradually levels off by approaching 100 % (Fig. 2a). Presumably, the decreasing rate of coverage with time (Fig. 2b) is caused by increasing degrees of overlapping of individual indentations.
The effect of exposure time on the deflections of the various types of test strips is illustrated in Fig. 3.



a) Almen test strips

b) Al 2024-T4 test strips

Fig. 3: Test strip deflections vs. exposure time

Because of the low mass flow of $\dot{m}$ = 45 g/min, comparatively long exposure times were needed for reaching Almen intensities of 0.17 mmA and 0.47 mmN, respectively (Fig. 3a). Compared to the conventional Almen test strips (Fig. 3a), the deflections of the Al 2024-T4 test strips reach saturation somewhat earlier (Fig. 3b). Presumably, this is caused by the lower hardness of the aluminum strips which leads to larger indentations and faster developments of residual compressive stresses which mainly cause these deflections.
The shot peening-induced residual stress-depth profiles in Al 2024-T4 are given in Fig. 4 comparing the results for the conditions **LC**, **IC** and **FC**.

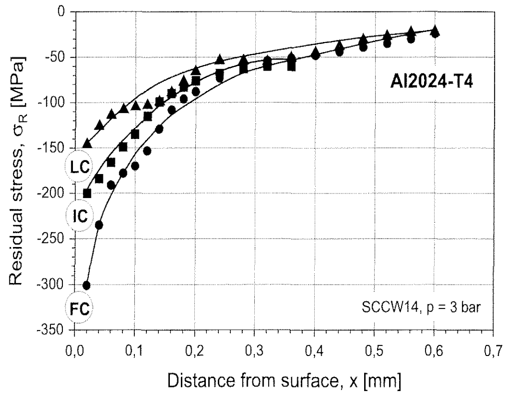


Fig. 4: Residual stress-depth profiles in Al 2024-T4 after shot peening with various degrees of coverage

With an increase in the degree of coverage from **LC** to **IC** and **FC**, the magnitude of the near-surface residual compressive stresses clearly increases. Although not demonstrated in the results from the incremental hole drilling procedure (Fig. 4), one should keep in mind that these are data from integrating over large surface areas and that the local residual stresses in **LC** and **IC** may largely vary due to incomplete coverage [3].

The surface roughness profiles (Fig. 5) clearly reflect the various degrees of coverage. Starting with the very low roughness of **EP**, an increase in coverage from **LC** to **IC** increases the frequency of occurrence of roughness peaks. At full coverage (**FC**), the roughness profile tends to saturate with regard to maximum roughness and frequency of occurrence.

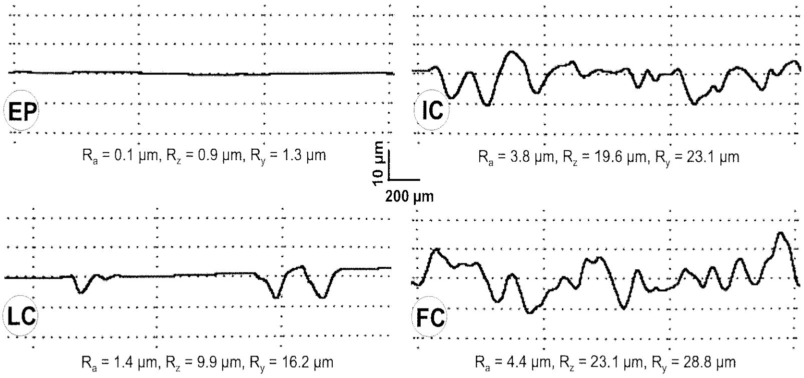


Fig. 5: Surface roughness profiles of the various degrees of coverage in Al 2024-T4

The effect of the degree of coverage in shot peening on the fatigue life at stress amplitudes of 300, 250 and 238 MPa is illustrated in Fig. 6.

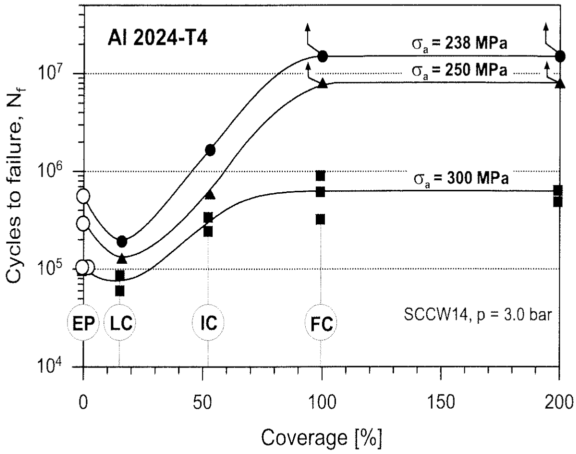


Fig. 6: Fatigue life (R = -1) of Al 2024-T4 vs. degree of coverage (rotating beam loading)

Starting with EP, the fatigue life at the various stress amplitudes first decreased at low coverage followed by marked improvements as the coverage increased. No further improvements in fatigue life were observed by increasing the coverage from 100 to 200 %, i.e., by doubling the exposure time (Fig. 6).

While the beneficial effect of increasing coverage on fatigue life was anticipated, the significant decrease in fatigue life from **EP** to **LC** (Fig. 6) was unexpected. Optical microscopy revealed that in **LC**, fatigue cracks nucleated even earlier than in **EP**. These cracks nucleated at single impacts and then propagated through un-peened regions (Fig. 7).

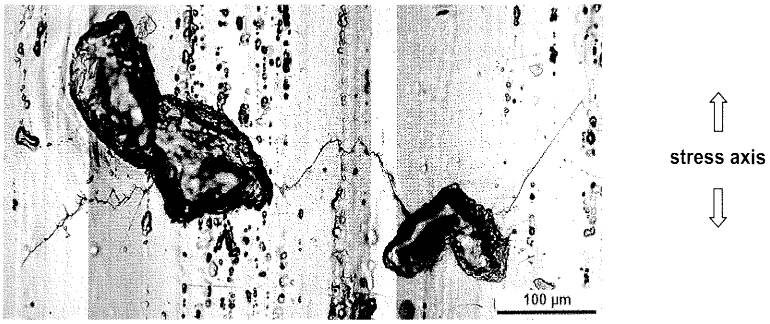


Fig. 7: Fatigue crack nucleation at single impacts (condition **LC**)

Thus, the poor fatigue performance of **LC** (Fig. 6) can be explained firstly by the stress concentration at the fairly irregular indentations caused by the SCCW 14 shot which obviously favors early crack nucleation (Fig. 7). Secondly, the residual compressive stresses in **LC** are not sufficiently high (Fig. 4) and are not homogeneously distributed to markedly retard early crack growth. By increasing the coverage degree from **LC** to **IC**, the residual compressive stresses increase and likely become more homogeneously distributed. Thus, micro-crack growth can now effectively be hindered. As a result, the negative effect of early crack nucleation is overcompensated resulting in improvements in fatigue life relative to **EP**. The retardation effect of residual compressive stresses on micro-crack growth is fully developed in **FC** resulting in most marked improvements in life (Fig. 6).

From the results shown in Fig. 6, the conditions **EP**, **LC**, **IC** and **FC** were taken for further fatigue testing. The S-N curves of these conditions are illustrated in Fig. 8.

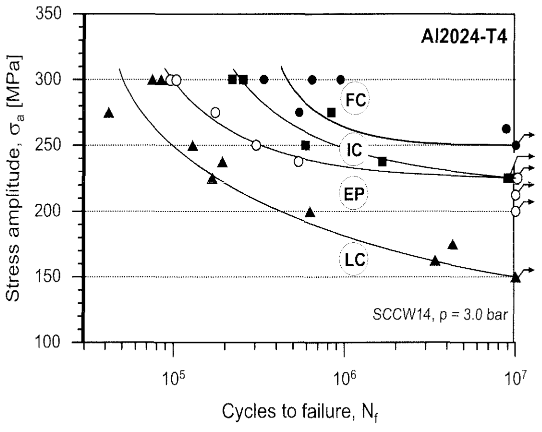


Fig. 8: S-N curves (R = -1) of Al 2024-T4 in rotating beam loading, effect of degree of coverage

As already indicated in Fig. 6, the fatigue performance of **LC** is by far the worst exhibiting a drop in the 10^7 cycles fatigue strength from 225 MPa (**EP**) to 150 MPa (Fig. 8). Comparing the fatigue behavior of **LC** with **EP**, it is seen that the HCF performance is more detrimentally affected than the fatigue life at high or intermediate stress amplitudes (Fig. 8), this again indicating the loss in resistance to fatigue crack nucleation resulting from the stress concentration at the single impacts. Neglecting residual stress effects in **LC** and taking the ratio $\sigma_{a10}{}^7$ (**EP**)/$\sigma_{a10}{}^7$ (**LC**), this stress concentration in fatigue amounts to 1.33.

As opposed to **LC**, the fatigue performance of **IC** is already superior to **EP** while **FC** results in the highest S-N curve (Fig. 8). Similar results are reported in [4]. It is argued that this improvement in fatigue performance is mainly caused by the full development of residual compressive stress fields in the surface area of **FC**.

SUMMARY

The results of the present investigation on Al 2024-T4 can be summarized as follows:

- Peening with SCCW14 to low (16%) coverage can markedly decrease the HCF strength. This effect is caused by early crack nucleation at individual shot indentations. Residual compressive stresses are barely developed and thus, can hardly hinder micro-crack growth from the surface into the interior.
- Peening to intermediate (53%) coverage already leads to improvements in fatigue performance. The development of residual compressive stresses is able to significantly hinder micro-crack growth which overcompensates early crack nucleation and increases the fatigue life.
- Peening to full (≥100%) coverage leads to a full development of residual compressive stresses. Therefore, micro-crack growth from the surface to the interior is most markedly suppressed resulting in highest improvements in fatigue life and fatigue strength.

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