# EFFECT OF SHOT PEENING ON RESIDUAL LIFE OF FATIGUE PRE-DAMAGED 2024 Al

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## ABSTRACT

The residual life of fatigue pre-damaged 2024 Al in the stretched and naturally aged condition T3 was evaluated after shot peening. Depending on the shot peening intensity, fatigue induced initial crack depths of up to 1500 μm did not reduce residual life compared to the crack-free electropolished reference. The results are explained in terms of the threshold behavior of surface cracks as affected by the interaction of the crack tip stress field and the local residual stress values below the surface.

## KEYWORDS

Fatigue pre-damage, shot peening; Almen intensity; dislocation density; residual compressive stress; microcrack propagation.

## INTRODUCTION

Previous work on 2024 Al [1 - 3] has shown that shot peening increases the fatigue life mainly by introducing residual compressive stresses in near-surface regions which hinder microcrack growth. While shot peening is usually applied as the final surface treatment of structural parts before they are put in service, parts already in service can be shot peened or re-peened after an inspection or an overhaul. It was reported in [4] that shot peening is able to "rejuvenate" fatigue damaged components. However, the analysis was made on changes in dislocation density and residual stresses without taking into account the propagation behavior of surface cracks. Regarding service behavior under fatigue conditions, it would be advantageous to know to what extent shot peening is still effective in prolonging fatigue life if cracks are already present. The resulting fatigue performance should then depend on both crack size and peening intensity, i. e., depth of the residual compressive stress field.

## EXPERIMENTAL PROCEDURE

The 2024 alloy was received as an extrusion in the stretched and naturally aged T3-condition. Tensile properties are listed in Table 1.

Table 1 - Tensile properties of 2024 Al (T3)

| $\sigma_{0.2}$ (MPa) | **UTS** (MPa) | **$e_u$** (%) | **El** (%) |
|---|---|---|---|
| 350 | 440 | 6.6 | 12.3 |

To produce the desired initial crack sizes, electrolytically polished hourglass shaped specimens (gage diameter 4 mm) were cyclically loaded with the rotating beam method (R = -1) at different stress amplitudes to various fractions of the fatigue life. While cycling at stress amplitudes of 250 and 225 MPa led to the nucleation of numerous surface cracks which interacted after propagation for only short distances, cycling at 200 MPa induced only few cracks which individually propagated for long distances. Thus, all further specimens were fatigue pre-damaged at 200 MPa. The resulting maximum surface crack length, **2c**, was monitored for each specimen. The corresponding crack depth **a** was calculated via the ratio **a/2c** = 0.40 which was experimentally verified. Specimens were fatigued at this stress amplitude of 200 MPa to various fractions of the expected life in order to adjust surface crack lengths ranging from 500 to 3000 µm. After adjusting these surface crack lengths, part of the specimens were shot peened and fatigue testing was continued for the shot peened and the reference conditions at a higher stress amplitude of 275 MPa until final failure occured.

Shot peening was done using Almen intensities ranging from 0.20 to 0.36 $mmA_2$. Details of the shot peening treatment are listed in Table 2.

Table 2 - Details of the direct pressure shot peening treatment utilized on 2024 Al

| shot size (mm) | shot type (cast steel) | inner nozzle diameter (mm) | working distance (mm) | revolutions/ time ($s^{-1}$) | exposure time (s) |
|---|---|---|---|---|---|
| 0.8 | S 330 | 8 | 45 | 1 | 60 |

Residual stresses were measured on a X-ray diffractometer with Ni-filtered Cu-K$\alpha$ radiation. Measurments were done on the (422) lattice planes of the fcc single crystals. Stresses were calculated by the $\sin^2\psi$-method proposed by Macherauch [5] assuming a Young's modulus of 71 GPa and a Poisson's ratio of 0.34. Dislocation densities were studied by TEM.

## EXPERIMENTAL RESULTS AND DISCUSSION

The microstructure of 2024 Al is shown in Fig. 1 presenting the typical pancake grain structure. The S-N curve for the electrolytically polished reference of 2024 Al-T3 can be seen in Fig. 2. The $10^7$ fatigue strength is around 150 MPa. Microcrack growth as tested at a stress amplitude of 200 MPa is shown in Fig. 3. From the crack growth seen in Fig. 3a, the surface crack length 2c is plotted in Fig. 3b. Obviously, microcrack propagation rather than crack nucleation consumes most of the lifetime at this stress amplitude.

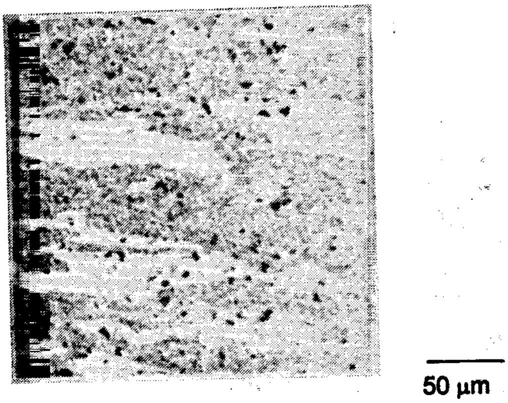


*Fig. 1: Microstructure of 2024 Al*

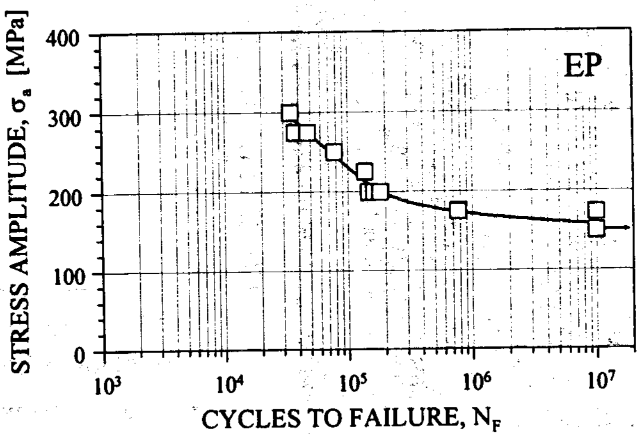
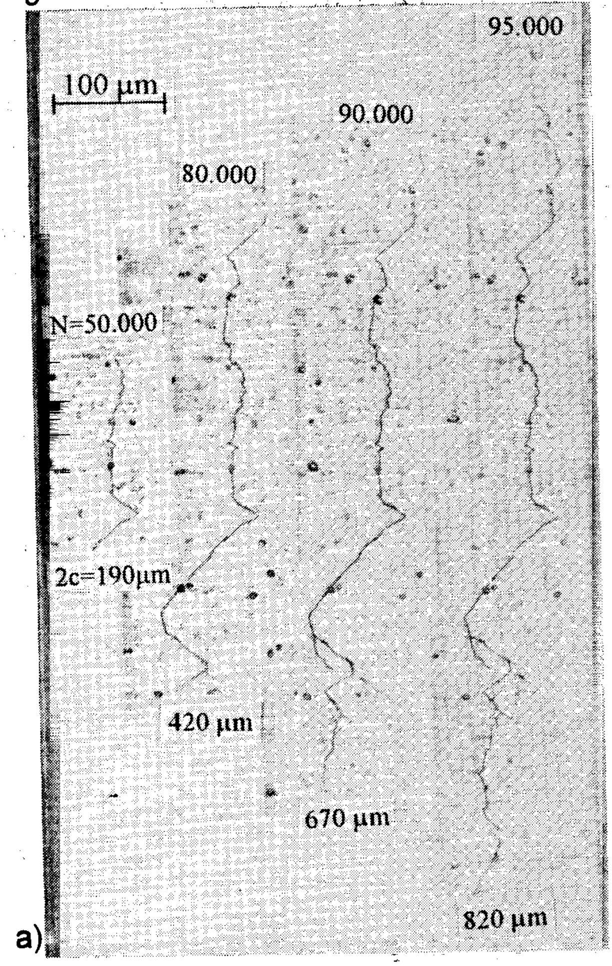
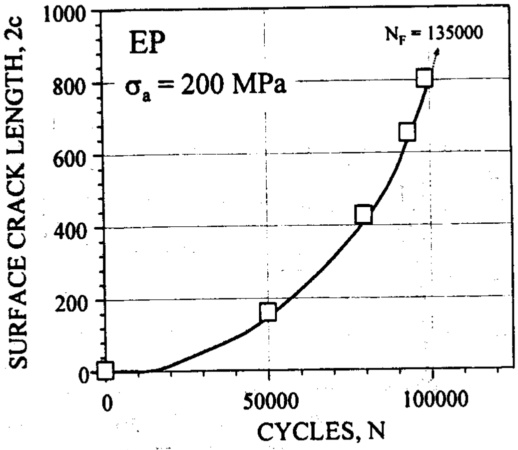


*Fig. 2: S-N curve for the electrolytically polished reference (R = -1, air)*





b) Surface crack length 2c vs. number of cycles (see Fig. 3a)

*Fig. 3: Microcrack growth in electropolished 2024 Al (T3) ($\sigma_a$ = 200 MPa)*

An example of the shape of a fatigue induced surface crack is seen in Fig. 4. The aspect ratio a/2c = 0.4 was found on most cracks. The testing sequence consisting of fatigue pre-damaging at 200 MPa and further cycling at 275 MPa is shown schematically in Fig. 4.

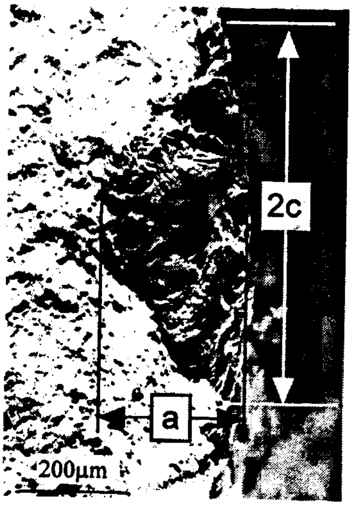


*Fig. 4: Crack shape (SEM)*

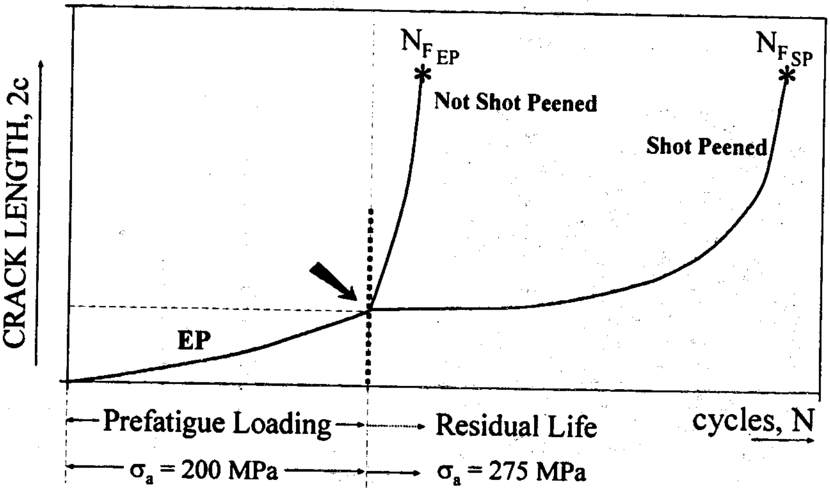
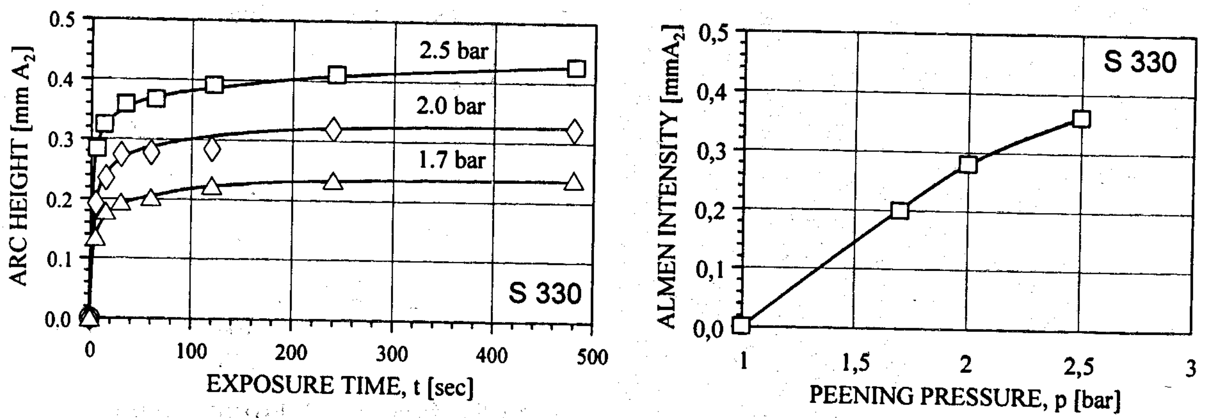


*Fig. 5: Testing sequence in 2024 Al (schematic)*

Shot peening parameters of the direct pressure peening device are given in Fig. 6. Depending on the peening pressure, saturation values in arc height of the Almen strips are reached within short exposure times (Fig. 6a). These saturation values (=Almen intensities) are plotted vs. peening pressure in Fig. 6b. For all fatigue specimens which were to be shot peened, an exposure time of 1 min was found to be sufficient for ensuring a 100% coverage.



*a) Arc height vs. exposure time*

*b) Saturation values vs. peening pressure*

*Fig. 7: Shot peening parameters in direct pressure peening*

Roughness values are shown in Fig. 7, indicating very smooth surfaces for the reference EP and increasing roughness values $R_a$ and $R_z$ with increasing Almen intensity.

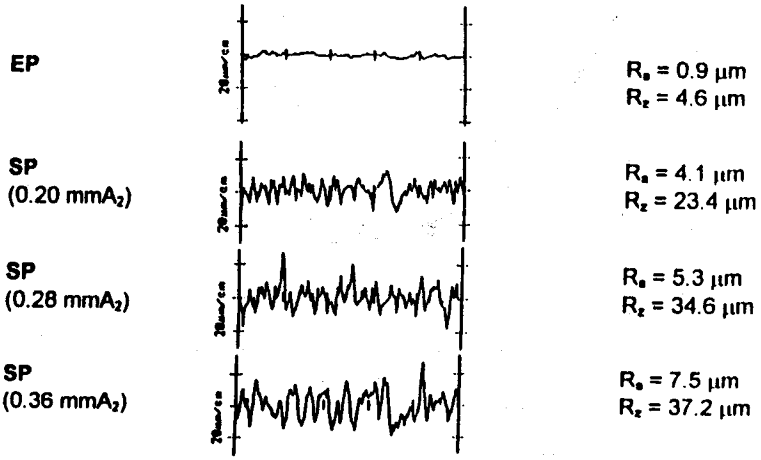
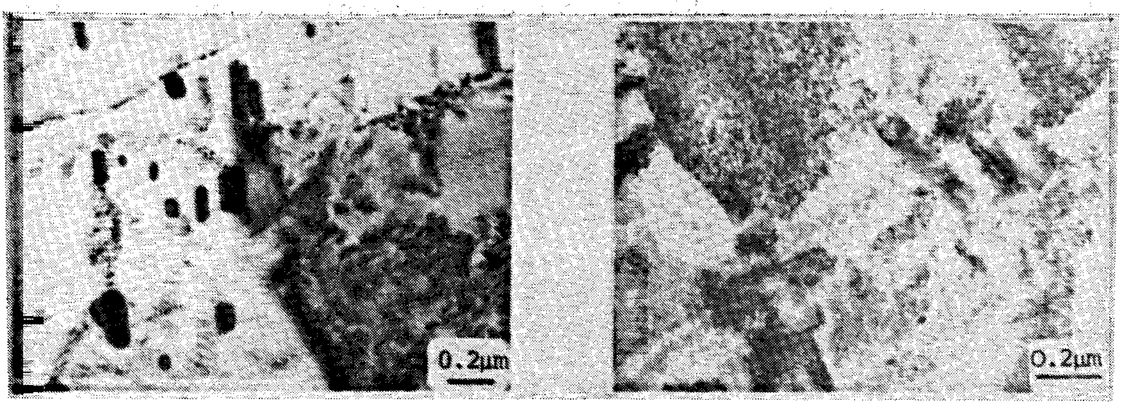


*Fig. 7: Roughness profiles and values for the various conditions*

The shot peening induced plastic deformation increases the near surface dislocation density and develops residual compressive stresses, whose interaction with surface cracks is important for understanding the results of this study. The TEM microstructures of the reference and the shot peened condition (distance from the surface about 50 µm) are shown in Fig. 8. Compared to the undeformed microstructure with its low dislocation density (Fig. 8a), the dislocation density drastically increases after shot peening (Fig. 8b). A typical dislocation density profile is given in Fig. 9. Microhardness measurements also indicated that the shot peening induced depth of plastic deformation amounts to about 400 µm for an Almen intensity of 0.20. Since the depth of the compressive stress field is similar to the depth of plastic deformation, the residual stresses also extend to depths equal or greater than 400 µm depending on Almen intensity.



a) Reference

b) Shot peened
(distance about 50 µm from surface)

Fig. 8: TEM microstructures of 2024 Al

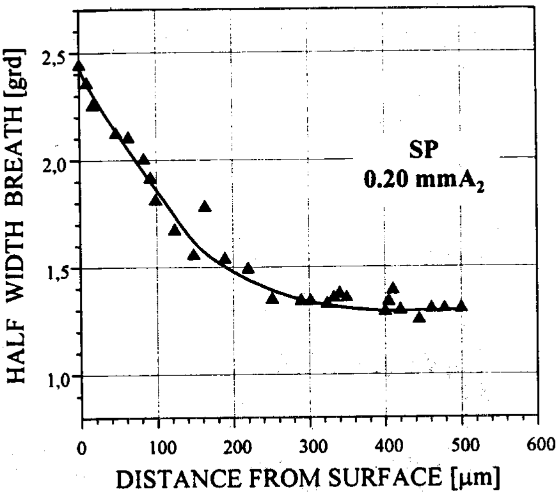


Fig. 9: Dislocation density profile [2]

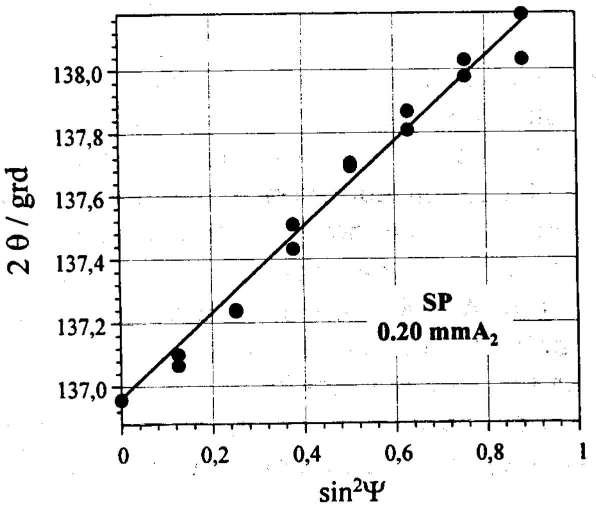


Fig. 10: $2\theta$ - $\sin^2\psi$ dependence

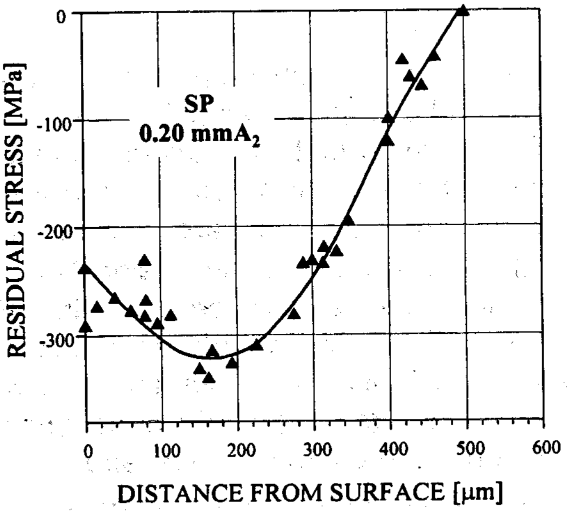


Fig. 11: Residual stress profile [2]

X-ray measurements indicated a linear relationship between Bragg angle $2\theta$ and $\sin^2\psi$. An example is shown in Fig. 10 for the as-peened surface. Only slight differences in the stress values were calculated by various evaluation methods as shown in Table 3.

Table 3 - Calculated stress values in the as peened surface of 2024 Al

| Method | Stress /MPa |
|---|---|
| Parabola | -244.0 |
| Center of Gravity | -251.6 |
| Cross Correlation | -249.8 |

After removing of surface layers by electropolishing, the residual stress profile could be evaluated (Fig. 11). The depth of residual compressive stresses equals the depth of induced plastic deformation (compare Fig. 11 with Fig. 9).

S-N curves of the reference as well as the crack-free heavily shot peened (0.36 mm $A_2$) condition are shown in Fig. 12. On average, the increase in lifetime due to shot peening is greater than an order of magnitude. This improvement was found to be mainly caused by hindering the propagation of surface cracks owing to residual compressive stresses which shield the crack tip [1-3]. An example of microcrack growth in the shot peened and reference conditions is shown in Fig. 13. At a given stress intensity, crack growth in the shot peened condition was found to be an order of magnitude slower than in the reference [1].

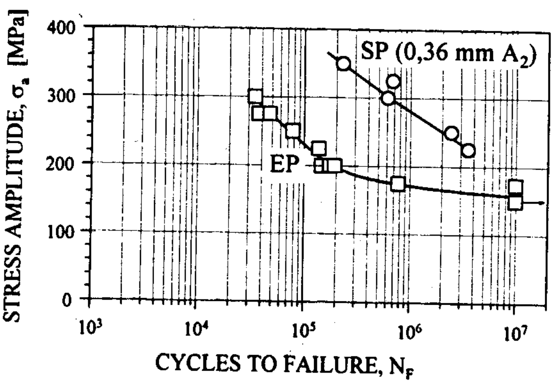


*Fig. 12: S-N-curves of 2024 Al-T3: Effect of heavy shot peening on virgin specimens*

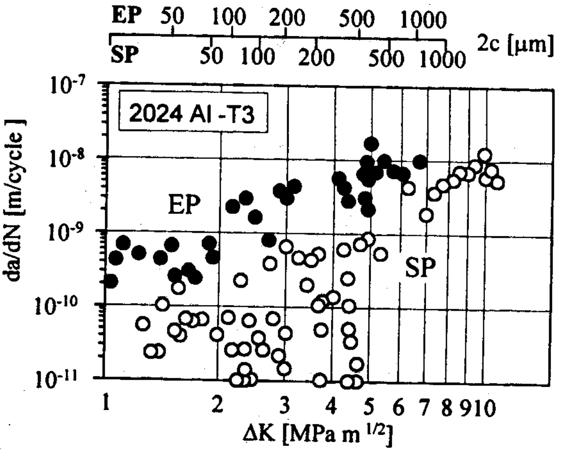


*Fig. 13: da/dN-ΔK curves of microcracks in 2024 Al-T3 comparing reference (EP) and shot peened (SP) conditions, rotating beam loading [1]*

The effect of fatigue induced initial crack depths **a** on residual life at 275 MPa of the various conditions is plotted in Fig. 14. Starting with the crack-free condition, the lifetime in the reference EP (Fig. 14a) first decreases only slightly followed by a severe drop for crack depths above 600 μm.

A comparison of the fatigue life of this reference with the various shot peened conditions is shown in Fig. 14 b, c and d. While the improvement of the fatigue life of crack-free shot peened specimens seems to be independent of Almen intensity (Fig. 14, compare b with c and d), for specimens with deeper cracks, the fatigue life clearly depends on Almen intensity. For example, the fatigue life for an initial crack depth of 1000 μm varies from $N_F$ = 5000 to $N_F$ = 300000 cycles depending on Almen intensity.

These results are summarized in Fig. 15. The fatigue life of the crack free reference is met by specimens shot peened with an Almen intensity of 0.20, 0.28 and 0.36 for initial crack depths of 600, 1250 and 1500 μm, respectively (see arrows in Fig. 15). Interestingly, shot peening improves the fatigue life even if part of the crack tip in the specimen interior has left the residual compressive stress field. For example, cracks up to depths of 1500 μm are still retarded after shot peening with an Almen intensity of 0.36 mm $A_2$ (Fig. 14d) although the residual compressive stress field extends to a depth less than 1000 μm. This can be explained by the slower crack growth of the crack front in near surface regions resulting in retardation of the overall growth of the entire crack front [6].

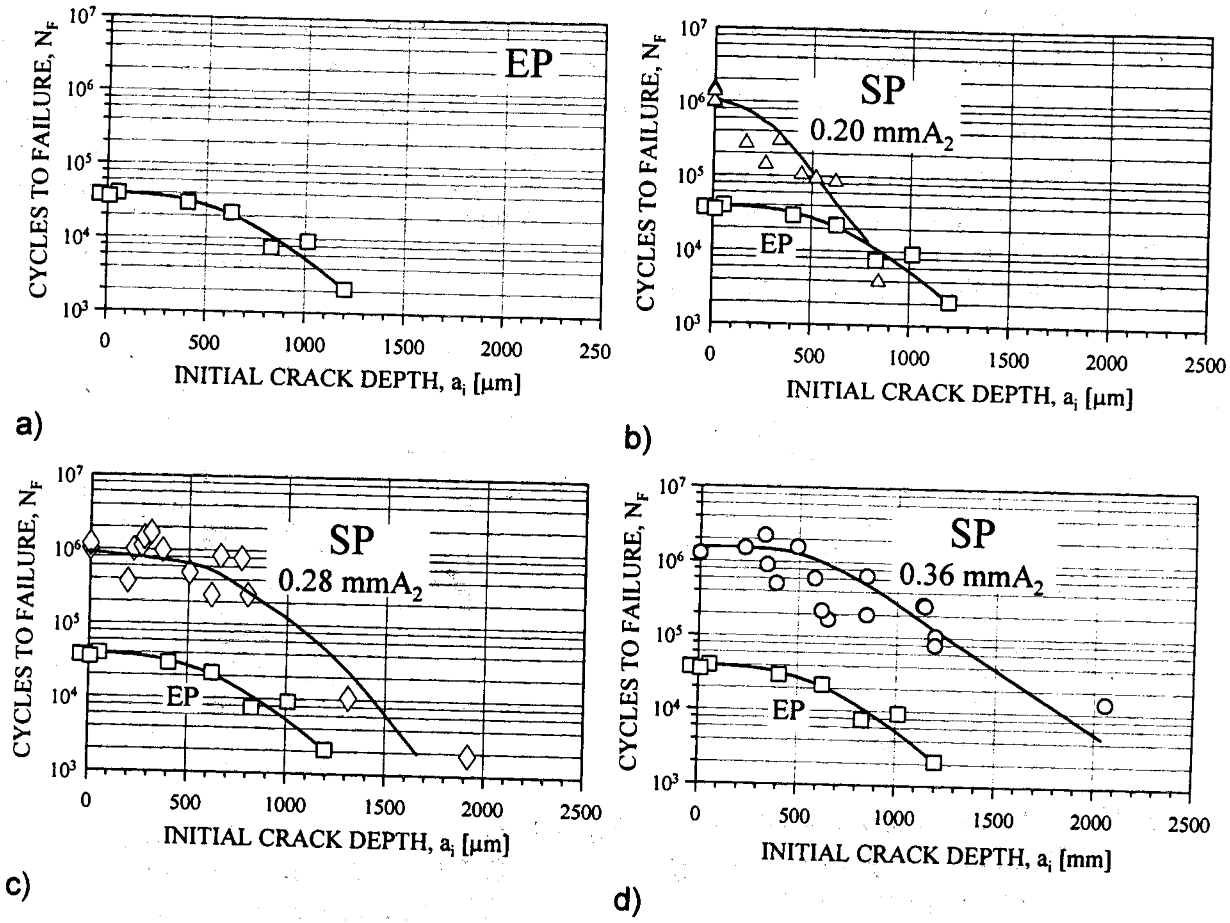


*Fig. 14: Effect of initial crack depth on residual life in the a) reference (EP) and the various shot peened conditions: b) 0.20 $mmA_2$; c) 0.28 $mmA_2$; d) 0.36 $mmA_2$*

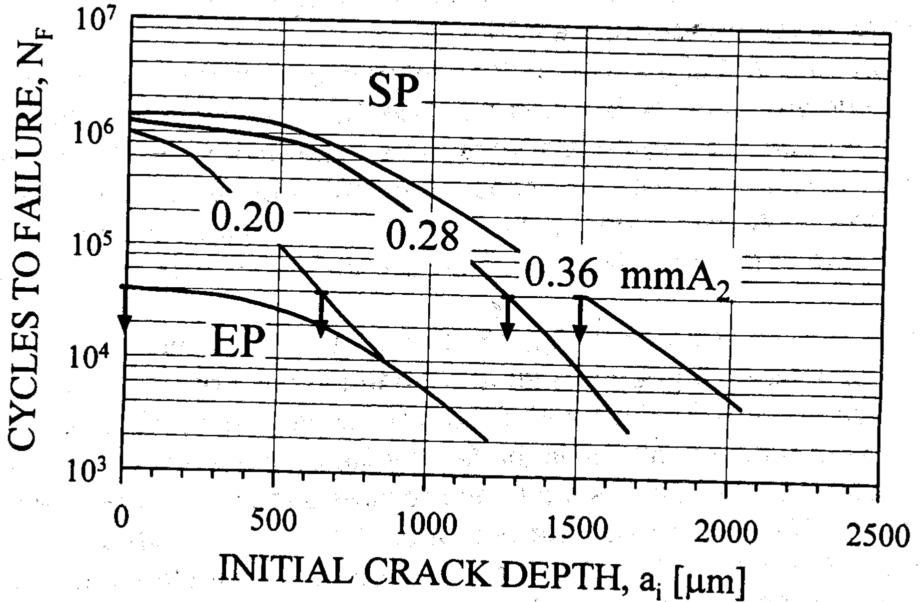
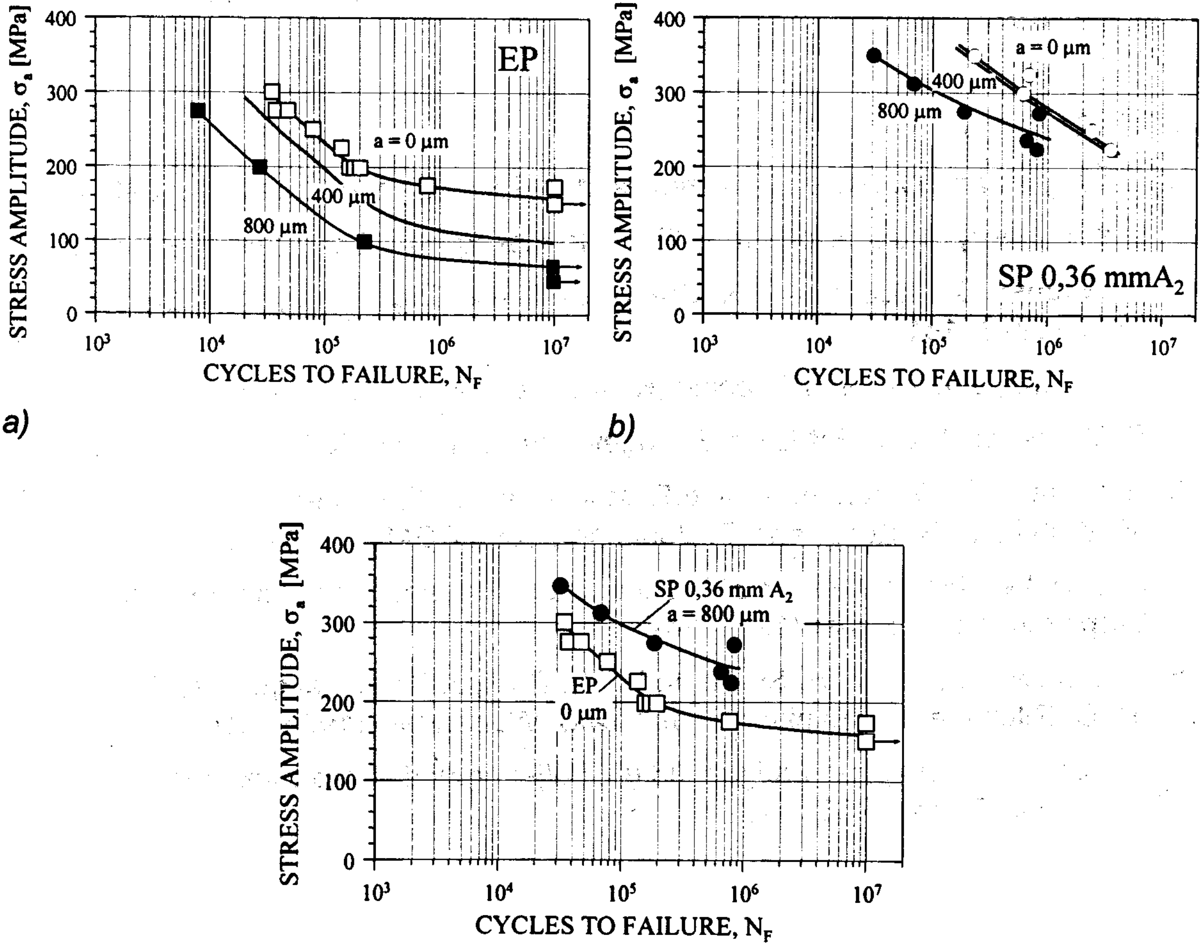


*Fig. 15: Comparison of the fatigue life of the reference (EP) with the various shot peened conditions (arrows indicate crack sizes at constant life of $N_F = 4 \times 10^4$)*

The effect of fatigue induced initial crack depths on the S-N curves of the various conditions is shown in Fig. 16. For the reference (Fig. 16a), a 400 μm initial crack depth already clearly lowers the S-N curve and reduces the endurance limit from 150 to about 100 MPa. An additional loss in fatigue performance is found for an 800 μm deep initial crack. The endurance limit is further reduced to about 75 MPa. This stress value corresponds to a threshold $\Delta K_{th}$ of roughly 3 MPa $m^{1/2}$ which is in good agreement with threshold values measured on long through-cracks in C-T specimens in this material [7]. While microcracks in 2024 Al are known to propagate at stress intensity values as small as 1 MPa $m^{1/2}$ (Fig. 13), the threshold value of 3 MPa $m^{1/2}$ indicates that the small crack effect is already absent in 2024 Al for cracks of the order of 1 mm [8].

For shot peened specimens (Fig. 16b), the same 400 μm deep crack does not change the S-N behavior of crack-free shot peened specimens whereas a 800 μm deep crack clearly reduces life, particularly at high stress amplitudes [9]. However as seen in Fig. 16c, shot peening of specimens with initial crack depths of 800 μm results in a S-N performance that is still significantly superior to the crack-free reference condition.



a)

b)

c)

*Fig. 16: Effect of initial crack depths on S-N curves in shot peened and reference conditions*

## SUMMARY

The results of the present study clearly show that shot peening of 2024 Al is particulary effective if cracks are already present. Unlike the situation in the not shot peened reference, cracks up to certain initial depths did not reduce residual life of shot peened specimens. These initial crack depths depend on the Almen intensity: the deeper the initial cracks, the higher the Almen intensity necessary for compensation. For example, initial cracks as deep as 400 µm did not reduce the residual life of specimens shot peened with the highest Almen intensity (0.36 $mmA_2$) utilized in this study. These results are explained in terms of the interaction of the shot peening induced residual compressive stress field with the local stress field of the crack front. Surface cracks will not propagate as long as the superimposed (residual + applied) stress intensity is below the threshold stress intensity.

## ACKNOWLEDGEMENTS

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