Optimization of Shot Peening to Improve the Fatigue Strength of Ti-6Al-4V

H.E. Franz, A. Olbricht, Messerschmitt-Bölkow-Blohm GmbH,
Central Laboratory, Ottobrunn, West Germany

Introduction

Reducing airframe weight is an extremely important consideration in the engineering of both military and commercial aircraft. Apart from static strength, the primary concern in aircraft engineering is fatigue strength, which, if improved, can mean significant savings in airframe weight. The fatigue strength of components can be improved in specific instances by shot peening. The chief aim of this study was to optimize the shot peening process to improve the fatigue strength of the titanium alloy Ti-6Al-4V. According to the literature, the peening of titanium alloys is a particularly sensitive process and has also be known to result in reduced fatigue strength (2). A further important goal was to learn the mechanism effecting the change in fatigue strength. Practice has shown that fatigue strength is dependent upon the type of cyclical loading, component form, material and certain secondary factors (1). One of these factors is the surface, which has been subjected to various treatments and processes and provided with protective coatings.

Shot peening changes the properties of near-surface layers, depending upon the condition of the material. The extent of the change can be determined in terms of certain characteristic values or parameters, and is also related to the original values for these parameters. The three most important parameters are: residual stresses, work-hardening and surface topography or morphology (1,3). Also to be taken into consideration are phase transformations and the implantation of shot-peening media. According to Wohlfahrt (3), changes in parameters, whether positive or negative, are in part responsible for the change in fatigue strength, depending upon the material's prior condition and the type of stress applied. The influence of microstructure on fatigue strength is well-known. By cutting all the specimens from a plate in essentially the same way, it was ensured that the microstructure was approximately the same in all the specimens and would manifest itself solely in the statistical distribution of fatigue strength values.

Specimen material

Test specimens were cut from 12 x 1000 x 2000 mm plates of ($\alpha+\beta$) titanium alloy Ti-6Al-4V (3.7164.1) in an "annealed" state.

Table 1: Alloy composition

Al	V	Fe	02	N2	C	H
6,2	4,0	0,13	0,18	0,01	0,01	0,006

There was no marked texture.

Specimen shape: Waisted smooth specimens: 110 x 24 x 6 mm, radius 45 mm ($\alpha_K = 1$)
Notched specimens: 110 x 16 x 8 mm, notch radius 1.8 mm ($\alpha_K = 1,6$)

The specimens were cut from the middle of the plate's thickness, the longitudinal axes of the specimens coinciding with the longitudinal axis of the plate. The specimens were finished using plain cutters for opposed milling (140 rpm, feed: 70 m/min).

Shot Peening

The specimens were shot-peened using compressed-air jets. We varied the peening media, Almen intensity (peening pressure) and the degree of saturation. We employed three different types of peening media: steel shot (ρ=7.8 g/cm^3), glass beads (ρ=2.4 g/cm^3) and ceramic peening medium (ρ=3.85 g/cm^3). The last consists of a bi-phase material, about 67% of which is a crystalline ZrO_2-phase and about 33% of which is composed of an amorphous SiO_2-phase. The ceramic peening medium originally used (ER120G) is referred to in the following as "old". Later we employed yet another ceramic peening medium, a new ceramic which we will refer to as zirshot, which contains a higher proportion of spherical shot, since is better screened, than does the original ceramic medium.

Table 2 shows the results for the individual peening processes. A total of sixteen peening processes were applied to smooth specimens and two further processes to notched specimens.

Table 2: Peening Processes

Specimen shape	Peening media	Particle size [µm]	Almenintensity	Degree of saturation	Number of cond.
Smooth specimen	Glass	180-300	0,15N/0,25N	1x98%	2
	Steel shot	400-500(S170) 1000 (S390)	0,15A/0,30A(0,40A	2x98% to 3x98%	5
	Steel shot+pol.	1000 (S390)	0,15A	2x98%	1
	Steel+Ceramics (old)	400-500(S170) 425 - 600	0,30A+0,20N	2x98% + 1x98%	1
	Ceramics (old)	425 - 600	0,20N/0,15A/0,20A	1x98%	3
	Ceramics (new)	425 - 600 850 - 1180	0.25N/0,15A/0,20A		4
Notched α_K=1,6	Ceramics (new)	150 - 210	0,10A/0,15A	1x98%	2

Properties Following Shot Peening

The depth distribution of residual stresses and line broadening (FWHM) of the diffraction profile were radiographically determined for each peening specimen as a measure of the specimen's degree of work-hardening. We also determined surface hardness and then surface morphology by means of depth of roughness (R_a, R_t), roughness profile measurements and scanning electron microscope pictures. Table 3 shows the results for the depth of roughness measurements. Depth of roughness increases for all types of peening media with increasing Almen intensity. The effect of increasing shot diameter in the case of zirshot, however, was opposite to that of steel shot: while depth of roughness increases as steel shot of larger diameter is used, it decreases as the diameter of zirshot is raised. This new ceramic material also produced roughness of less depth than the old one.

Table 3: Depth of Roughness Following Shot Peening

Peening media	Roughness		Hardness	α_K
	Ra [µm]	Ra [µm]	HV30 kp	
mashined	0,60	4,7	337 ± 9	
Glass	0,63-0,67	4,8-5,0	334 ± 4	
Steel	0,82-2,0	5,6-14,5	344-370	1
Ceramics - old	0,74-1,70	4,8-10,6	340-350	
Ceramics - new	0,58-1,12	4,4-8,80	330-350	
In the notch	1,5	13,80	375 ± 8	1,6

Graphs of residual-stress depth distribution and work hardening show two similarities: work hardening is always greatest at the surface, and the depth of residual stresses always corresponds roughly to the hardened layer. Surface compression stresses are in the relatively limited range from 520 to 610 N/mm^2 (50 to 60% of the yield strength). The maximum compression stresses, which are located from 20 to 160 µm below the surface, range from 610 to 900 N/mm^2 (60 to 90% of the yield strength).

The left-hand graph of Fig. 1 compares stress-depth distribution curves following steel shot peening at different Almen intensities. At the right, peening with steel and with ceramic shot are compared. Fig. 2 shows the maximum residual compression stresses that can be reached with the different peening media at increasing Almen intensities.

Fig. 1:

Tiefenverteilungskurven der Eigenspannungen und der Verfestigung(HWB)

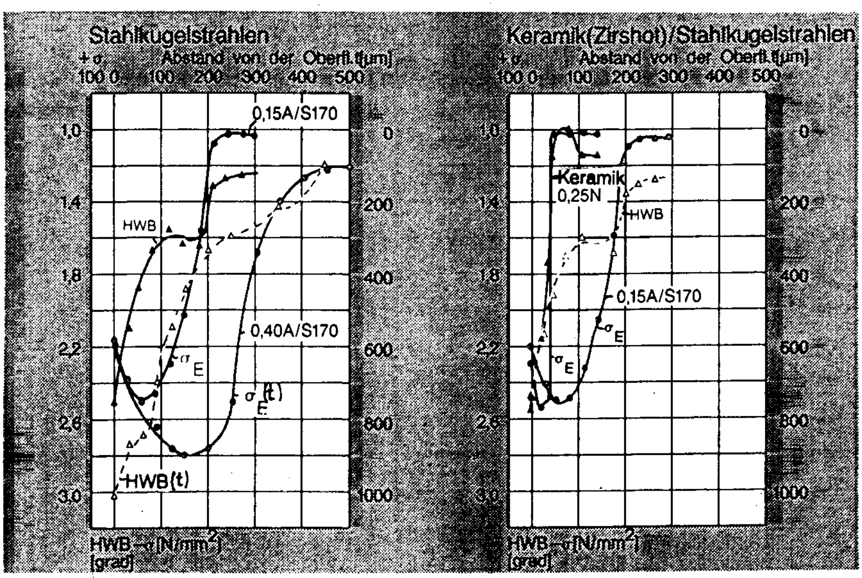
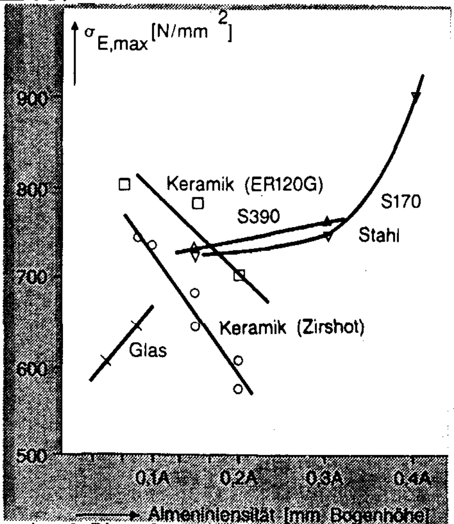


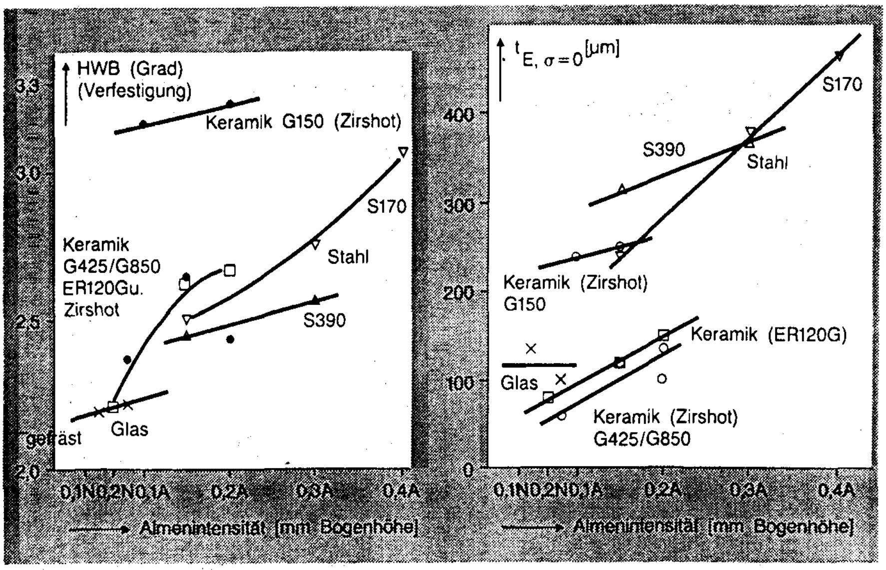
Fig. 2: **Maximale Eigenspannungen in Abhängigkeit von der Almen-intensität**



While the maximum residual compression stresses caused by using glass or steel as the peening medium increase as Almen intensity is raised, ceramic media have the opposite effect (Fig. 2), resulting in compression-stress maxima close to the surface and slight penetration depths. Similar results are obtained using glass beads, except that in this case the maxima of residual compression stress and the achievable degree of hardening are both lower than those attainable with ceramic peening media, as can be seen by a comparison with Fig. 3. Ceramic peening media yield high degrees of hardening comparable to those achieved using steel shot, but at lower Almen intensities. The hardness values plotted in the left-hand graph of Fig. 3 for the new ceramic medium G150 were found at the base of notches in notched specimens and can be attributed to the prevention of flow at the base of the notches. The right-hand graph of Fig. 3 suggests that the penetration depths of all peening media increase linearly as Almen intensity increases, but that the rate of increase is different for the various media.

Fig. 3:

Verfestigung/Eindringtiefe in Abhängigkeit von der Almenintensität



Determination of Fatigue Strength

Single-stage alternating bending tests were conducted on both the smooth and notched specimens at room temperature (R = -1). We used a resonance tester with a four-point bending apparatus. The Wöhler diagrams in Fig. 4 show the mean-value curves (50% probability of survival) obtained using a modified Weibull method. Results for smooth specimens are shown in Figs. 4 and 5. Using conventional peening media such as glass, steel or old ceramic, the fatigue limit can be improved from±410 to 470 N/mm², which is equivalent to an improvement of 15%. Using new ceramic or zirshot, however, the limit can be extended to±510 N/mm² for an improvement of 25%. In regard to the improvement in time strength (approx. 10^5 LW), conventional peening media improve fatigue life for the amplitude of ±550 N/mm² by a factor of 15, while zirshot improves it by a factor of 39. It should also be noted that, using conventional media, the highest fatigue limit can be achieved either with steel shot (0.15A/S170) or old ceramic (0.15A/ G425), whereas the greatest improvement in time strength is achieved using steel shot at high Almen intensity (0.40A/S170). In contrast, zirshot provides the greatest improvements in both fatigue limit and and time strength in one and the same peening process (0.25N/G425), as shown below.

Fig. 4

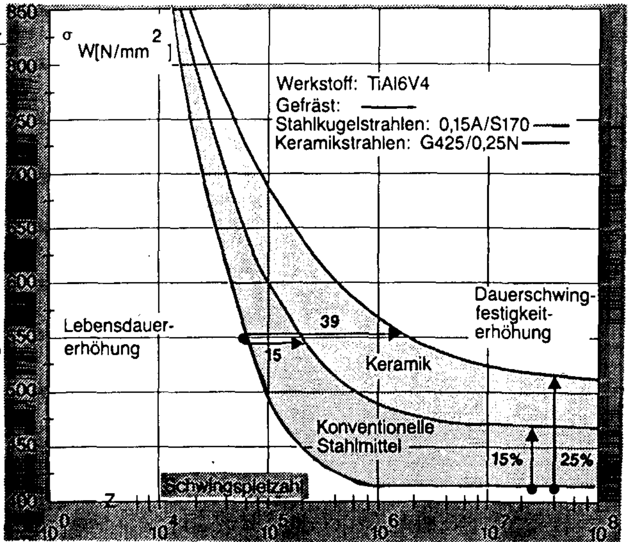


Fig. 5:

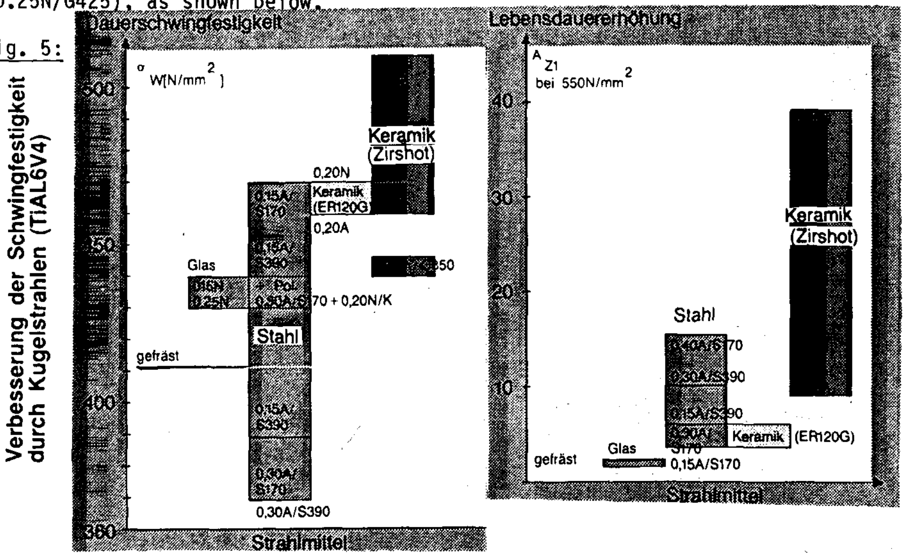


Fig. 5 indicates the results for the different peening processes. The fatigue limit and fatigue life yielded by each peening process is represented by a horizontal line within the bar indicating the peening medium (the bars do not represent deviation in fatigue limit or fatigue life). The fatigue life of notched specimens was lengthened by a factor of 40 (at an amplitude of ±450 N/mm^2) and the fatigue limit improved by 35%.

Effect of Parameters

For roughness depths of up to at least R_t = 14.5 µm, the effect of roughness on fatigue strength is compensated by simultaneous hardening or increased residual compression stresses. However, if two peening processes can be developed providing approximately the same degree of hardening and residual compression stresses, but different roughness depths, such as we have managed to do by polishing a steel-shot-peened surface, the effect of roughness depth can definitely be seen. Reducing the depth of roughness from 7.0 to 4.4 µm increased the fatigue limit from ±390 to ±430 N/mm^2 and the fatigue life from a factor of 3 to 5. In examining the effect of residual compression stresses and work hardening on fatigue strength, a distinction must first be made between time strength and fatigue limit. As soon as residual compression stresses exceeds 50% and the compression-stress maximum 60% of the yield strength, the fatigue limit can no longer be increased by raising residual compression stress. This applies both to conventional peening media and to zirshot. As can be seen from Fig. 6, however, the depth of the compression-stress maximum has an effect on the fatigue limit, i.e. the closer the compression-stress maximum is to the surface, the greater will be the improvement in the fatigue limit. The maximum residual compression stress has an effect on time strength. The functional relationship shown in the left-hand graph ($\sigma_{E,max} > 0.6\ R_{p0,2}$) of Fig. 7 is, however, considerably different for conventional peening media (line of low slope) than for zirshot (line of high slope). The penetration depth of the residual compression stress shown in the right-hand graph of Fig. 7 is similar, i.e. the greatest improvements in fatigue life can be achieved by peening with conventional media to attain high compression-stress maxima and high penetration depths of these compression stresses. This conclusion accords well with results obtained for heat-treated steel (350-500 HV). The increase in fatigue life is obviously more sensitive to peening with zirshot, in terms of both the compression-stress maximum and the penetration depth. Both low penetration depth and low compression-stress maxima are sufficient to retain high increases in fatigue life.

Fig. 6:

Schwingfestigkeit als Funktion der Tiefe des Druckspannungsmaximums

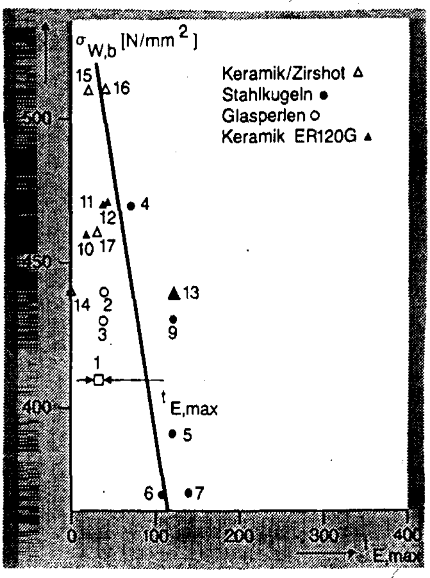
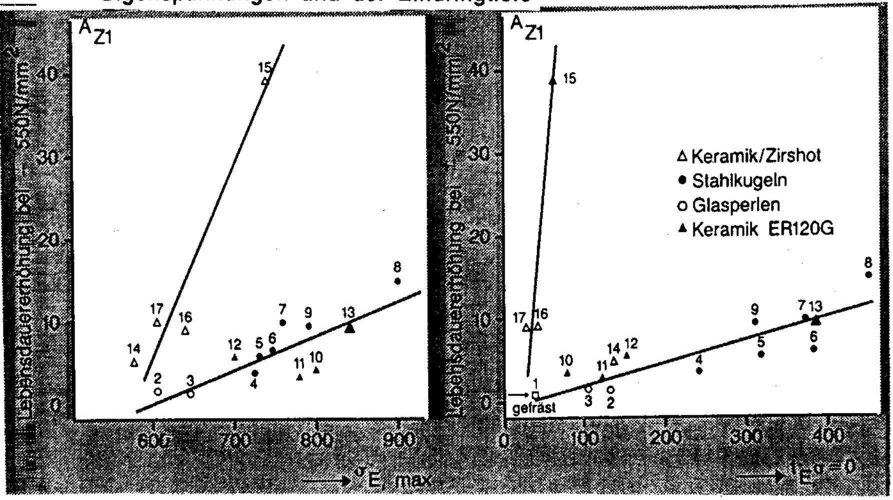


Fig. 7: **Lebensdauererhöhung als Funktion der Eigenspannungen und der Eindringtiefe**



If we now look at the third signficant parameter, work hardening, we can determine no pronounced effect on fatigue limit. Noteworthy here is that the negative effect of roughness depth is compensated by hardening. When conventional peening media are used, increases in hardening are accompanied by lengthened fatigue life or time strength. This does not hold true for zirshot.

Relaxation Measurements

The 25% improvement in fatigue limit provided by shot peening was not lessened by statistical loading, which consisted of creep loading at 50% of 0.2% yield strength for 1,000 hours.

Cyclic loading decreases residual compression stresses at the surface of smooth specimens as a function of amplitude. This decrease amounts to approx. 20% at ±500 N/mm and approx. 50% at±800 N/mm , and occurs chiefly during the first load alternation. Compression stresses then remain more or less unchanged until rupture occurs. The decrease in hardening is less significant, with a maximum of 25% at±800 N/mm .

Notched specimens provide different results: at notch bases there was practically no decrease in residual compression stress and an increase in hardening of 22%. The latter is probably due to the prevention of flow in the notch.

Discussion

First, let us examine the quantitative interaction of the three parameters using the empirical law of superposition (5):

$$\Delta\sigma_{W,b} = \alpha_1 \Delta R_t + \alpha_2 \Delta FWHM + \alpha_3 \Delta\sigma_{ES}$$

The coefficients α_1, α_2 and α_3 represent the sensitivity to roughness depth, hardening and residual stresses. $\Delta\sigma_{W,b}$ is the improvement in alternating bending strength brought about by shot peening. ΔR_t, $\Delta FWHM$ and $\Delta\sigma_{ES}$ are the changes in depth of roughness, hardening and residual compression stresses caused by shot peening. As determined by (4), among others, the coefficients for Ti-6Al-4V were found to be: α_1 = -6 N/mm^2 μm, α_2 = 0.52 N/mm^2 min and α_3 = 0.41. Strictly speaking, the coefficients would have to be a function of the two other parameters: $\alpha_1(FWHM, \sigma_{ES})$, $\alpha_2(R_t, \sigma_{ES})$ and $\alpha_3(R_t, FWHM)$.

For example, the sensitivity to roughness has a greater effect at $\Delta FWHM$, $\Delta\sigma_{ES} \neq 0$ than at $\Delta FWHM$, $\Delta\sigma_{ES} = 0$, so that the law can provide only a rough approximation.

For the material Ti-6Al-4V, it can be assumed that $\alpha_1 \doteq \alpha_2$ for the first approximation. This yields for $\Delta\sigma_{W,b} = \alpha_3 \Delta\sigma_{ES}$ with an α_3 of 0.1 - 0.2, which corresponds approximately to that of heat-treated steel (3). Thus Ti-6Al-4V possesses relatively high sensitivity to residual stresses, which correlates to the relatively strong mean-stress sensitivity of this material.

The results obtained for peening with zirshot do not entirely conform to our present knowledge of these parameters and their effects.

Any new concept would also have to take the following parameters into account: residual stress gradient, gradient of the local fatigue limit (cf. (4)), load stress gradient, location of initial fracture, quasistatic plastic deformation due to the first load alternation, plastic deformation due to cyclic loading (exceeding the cyclic yield strength), decreases in residual stresses and hardening, increases in new residual stresses (or extension of the layer effected by residual stresses), etc.

References

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