Improvement of the Fatigue Strength of Titanium Components under Variable Amplitude Loading

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1. Introduction

The improvement of fatigue behaviour by shot peening is due to two causes

- residual compressive stresses and
- increase of surface hardness

with the former being the more important at least for high strength materials. Against this, we have the deleterious effect of high surface roughness.

Repeated stresses are also known to alter the residual compressive stresses; how much, will depend on the sequence, magnitude and number of these applied stresses. Applied stress amplitudes and mean stresses may in addition set up compressive or tensile residual stresses of their own and may also alter the orginial yield strength of the material in question; how much, will again depend on their magnitude, sequence and number (this is in fact the basis of the so-called notch root damage accumulation hypotheses).

As will be understood from the above, the quantitative effect of shotpeening, combined with that of the applied stresses, on fatigue behaviour is a very complex one and it is difficult - if not impossible- to read across from one fatigue test program on shot peening to another.

A few general observations, however, may be in order here:

Unnotched areas of components are usually not fatigue critical; it is rather the notched sections which are.

Also, the local stresses due to the service loads are higher in the notched than in the unnotched sections and the effect of surface roughness on fatigue life is less deleterious in notched than in unnotched sections. Therefore the actual shot peened components (containing notches) should preferably be tested, if the results of the fatigue tests are to have any quantitative applicability to the actual service behaviour of the component.

If the components themselves cannot be tested (e.g. due to cost) at least notched specimens with similar stress concentration factors should be used and the actual stresses due to service loads should be simulated as closely as possible.

The latter aspect means that a meaningful fatigue test program requires prior knowledge of the application of the results. Two examples:

- A shot peened component which sees a practically unlimited number of nearly constant amplitude cycles in service, e.g. a crankshaft, has to be tested near the fatigue limit.
- A component for a tactical aircraft, which sees only about 10^5 cycles of variable amplitude loading during its lifetime, should be tested under such a stress spectrum.

Taking the above aspects into account, the following test program was put into operation by the author as part of a larger cooperative programm on shot peening of the titanium alloy Ti 6-4.

2. Test Program

2.1 Material and Test Specimens

The static properties and the composition of the material are shown in Table 1, the four point bending specimens in Fig. I.

Chemical Composition and Static Properties

Al	V	Fe	O_2	N_2	C	Ti	
6,2	4,0	0,13	0,18	0,01	0,01	Rest	weight %

Table 1

	$R_{p0,2}$ [MPa]	R_m [MPa]	Remarks
L direction	991	1041	arithmetic mean of 10 tests for each direction
LT direction	1091	1123	

The unnotched specimens were needed for comparison with the results of the other partners in the cooperative programm.

The notched specimen was designed to the following requirements:

On one hand the notch root hat to be $\gg$ 0,5 mm because of the envisaged shot size for Ti 6 - 4, of S 170 (0,5 mm). This relatively large radius was also expected to be easier to machine without residual stresses, a futile hope as it turned out later.

On the other hand, a stress concentration factor typical for modern, aircraft design was desired, i.e. K_t = 2,0 to 2,5. At the sheet thickness employed of 12 mm the net cross section also had to be above a certain size, i.e. the notch depth had to be $\leq$ 2,8 mm, because of the necessary test machine accuracy, especially for the variable stress amplitude tests.

These partly conflicting requirements led to the specimen dimensions shown in Fig. 1 with a maximum obtainable K_t = 1,6, somewhat lower than desired. The specimens for the cooperative program were at first manufactured by one firm. After the questionable results described below in chapter 3, the author's firm manufactured new notched specimens.

2.2 Applied Stresses, Stress Sequences, Stress Ratios

One aim of the test program was to investigate the effect of shot peening on fatigue life of Ti 6-4 for the structure of tactical aircraft. Therefore the "Falstaff" stress sequence / 1 / was used for the variable stress amplitude tests with notched specimens. The maximum stresses σ_{max} were selected such that 4 000 to 40 000 flights to failure resulted, corresponding to about $4 \cdot 10^5$ to $4 \cdot 10^6$ cycles.

Up to 8 specimens per parameter were tested at up to 4 different maximum stresses of the spectrum σ_{max}; this was sufficient for the determination of the fatigue life curves for a probability of survival of 50 per cent, because the scatter was quite small.

Besides, the usual SN-tests with notched and unnotched specimens were carried out at stress amplitudes resulting in failure between approximately $5 \cdot 10^3$ and $2 \cdot 10^6$ cycles. Up to 20 specimens were available per SN-curve for some test series; in these cases an improved version of the staircase method, developed in the author's department by Hück / 2 /, was employed to determine the fatigue limit at $2 \cdot 10^6$ cycles for 50 per cent probability of failure. In the finite life region a least squares regression analysis was used to draw the SN-curve through the test points at the same probability of failure. One example of such an SN-curve is shown in Fig. 2

If fewer specimens were available, the finite life region of the SN-curve only was determined. The result of the least squares regression, that is the position and slope as well as the "knee" of the SN-curve were also checked according to the author's experience.

The stress ratios for all constant amplitude tests was $R = \sigma_{min}/\sigma_{max} \approx +0,1$, similar to that in the Falstaff tests. The maximum nominal stresses were in all cases kept below the 0,2 per cent offset yield strength in bending of approximately 1800 MPa. However, the maximum local stresses at the notch root were above this value in some "Falstaff" tests (just like in a real aircraft structure), as well as in some constant amplitude tests.

2.3 Supplementary Measurements

The residual stresses after machining, i.e. without shot peening, as well as after shot peening were measured by X-ray on the surface of several notched and unnotched specimens. In a few shot peened specimens the residual stress distribution across the thickness was also measured, as well as the surface roughness before and after shot peening. Finally the decay (or otherwise) of residual stresses due to the applied stresses was determined in unnotched and notched specimens under constant and variable amplitude loading. All X-ray measurements were carried out by Dr. Franz at MBB, which the author gratefully acknowledges.

2.4 Shot Peening Parameters

In the course of the cooperative program the optimum shot peening parameters for unnotched specimens were determined to be 0,4 (mm) A2 Almen intensity with a shot size of S 170 and a coverage of 200 per cent. These were the parameters giving the optimum improvement in the finite life region under constant stress amplitudes at R=-1,0, although slighly lower intensities gave very similar improvements.

It was then assumed that these parameters would also be the optimum ones for the notched specimens at constant stress amplitudes and R = +0,1 as well as under the "Falstaff" sequence, an assumption which will be verified in 1984 by further tests.

At first, all shot peening was carried out at Professor Kopp's institute at the Technical University of Aachen. However, the later specimens manufactured by IABG were shot peened by the West German division of Metal Improvement Company in Unna, Germany. The choice of optimum shot peening parameters was left to them and, according to their long experience,they selected 0,25 - 0,30 (mm) A2 Almen intensity, 200 per cent coverage with a shot of size S 170 hard, i.e. a slightly lower intensity and hard shot (R_C 62) of identical size. The author gratefully acknowledges this assistance by Metal Improvement Company.

2.5 Test Machines

Most of the tests were carried out on a servohydraulic machine of ± 1 MN capacity built by IABG.

For the "Falstaff" tests, it was controlled by a Schenck-Computer.

In view of the questionable results described below, the command values given out by the computer were compared extensively (almost for every test) with the response values of the specimen. These comparisons of the loads always were o. k., i. e. they lay within allowable (narrow) tolerances.

3. Results

Due to the limited space available, not all the results obtained can be shown in diagram form, nor can they all be discussed in detail.

3.1 SN-tests

The SN-tests with unnotched, not shot peened specimens gave a fatigue limit in bending of about ± 350 MPa (approximately as expected); however, the slope of the SN-curve was extremely steep at k = 3,3. Shot peening resulted in the improvements in fatigue strength shown in Fig. 3.

The SN-curve of the notched specimens again had an uncommonly steep slope of k = 4,1. When they were tested in the shot peened conditions, it became immediately apparent that something was amiss, see Fig. 4: Shot peening lowered the fatigue strength in the finite life region; moreover, the two SN-curves crossed at around 10^5 cycles; beyond this number of cycles, shot peening resulted in improved fatigue strength.

Since similarly inexplicable results were obtained with "Falstaff" tests, see chapter 3.2, new notched specimens were manufactured by the IABG machine shop; about half of them were shot peened by Metal Improvement Company in Germany, as described in chapter 2.4. The results of the subsequent tests came out as expected, see Fig. 4: The slope of the SN-curve was normal at k = 7,4 for the shot peened and k = 6,7 for the not shot peened condition. There was also an improvement of the fatigue strength over the whole region of cycles tested.

To this date, all attempts to clear up the unexpected results decribed above have failed: The residual stresses on the surface of the notch root after machining for the faulty specimens were, if anything, lower than those of the IABG specimens (- 350 MPa as against -430 MPa). The surface roughness at the notch root (mean of at least 3 tests) was also lower than that of the IABG specimens at R_t = 2 µm, R_m = 0,1 µm as against R_t = 7 µm, R_m = 0,5 µm.

3.2 "Falstaff" Tests

The defective specimens in the not shot peened condition fell into two distinctive groups, one giving much longer fatigue lives, (by a factor of about 2,5) see Fig. 5. There was also a crossover of the fatigue life curves for the shot peened and the not shot peened condition as in the constant amplitude tests.

It was therefore concluded that the shot peened specimens must have come from the first, better, group of specimens.

The subsequent tests therefore were carried out with specimens manufactured by IABG (and shot peened by MIC). These results are also shown in Fig. 5: In the not shot peened condition, they practically coincided with the former second group; shot peening resulted in approximately doubling the number of flights to failure; this improvement of fatigue life is about equal to that under constant stress amplitude in the finite life range, see. Fig. 4.

4. Residual Stresses

The residual stress distribution across the thickness in an unnotched shot peened specimen is shown in Fig. 6.

The maximum compressive stress is about 700 MPa, or about 70 per cent of the yield strength. This is somewhat lower than in previous work of the author [3] where residual stresses of 100 per cent of the yield strength of the high-strength titanium alloy Ti 6-6-2 were reached by shot peening (the fatigue life improvement factor was also much higher in [3]).

5. Conclusions

- Manufacturing quality of the specimens is of utmost importance in a test program.
- Shot peening improved the fatigue life in the finite life region of the SN-curve by a factor of up to four (for unnotched specimens) and approximately two for notched specimens. The latter value also was obtained under flight-by-flight loading typical for a tactical aircraft.

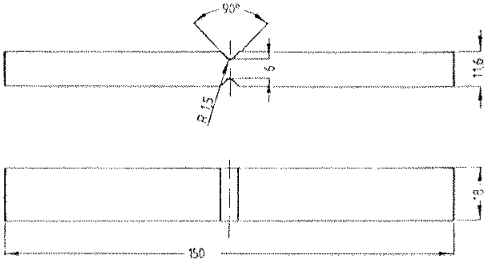
6. References

/ 1 / Aicher, W., J. Branger, G.M. von Dijk, J. Ertelt, M. Hück, J.B. de Jonge, H. Lowak, H. Rhomberg, D. Schütz, W. Schütz: Description of a Fighter Aircraft Loading Standard for Fatigue Evalution "Falstaff" (F+W, LBF, NLR, IABG) März 1976

/ 2 / M. Hück: Ein verbessertes Verfahren für die Auswertung von Treppenstufenversuchen, in: Neuere Erkenntnisse und Verfahren der Schwingfestigkeitsforschung, 6. Sitzung des Arbeitskreises Betriebsfestigkeit des DVM, Darmstadt, Mai 1981.

/ 3 / W. Schütz: Fatigue Life Improvement of High-Strength Materials by Shot Peening, in: First International Conference on SHOT PEENING, ICSP 1, Paris, Sept. 1981, Pergamon Press

Notched Specimen $K_t = 1{,}6$



Unnotched Specimen

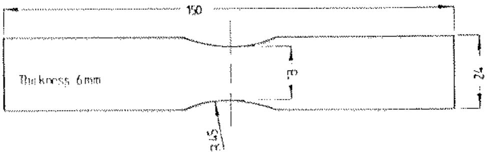


Fig. 1: Specimens

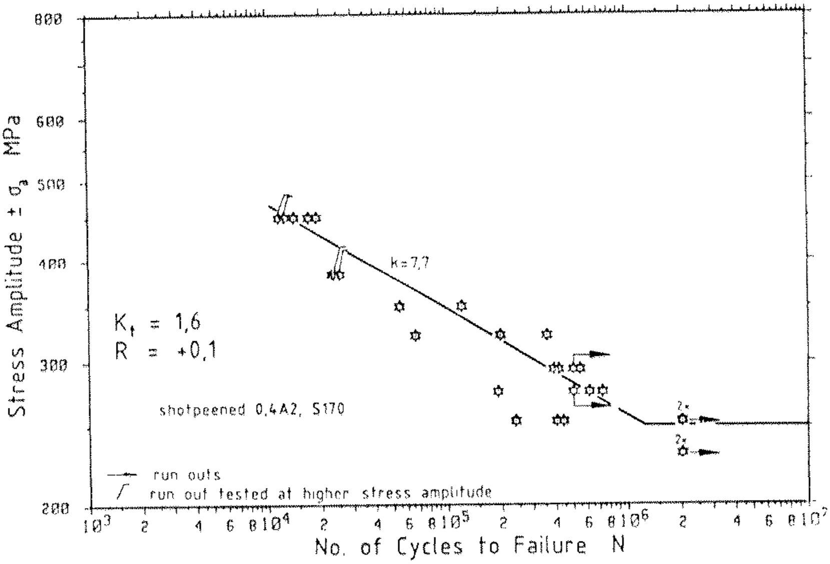


Fig. 2: Example of an SN-Curve

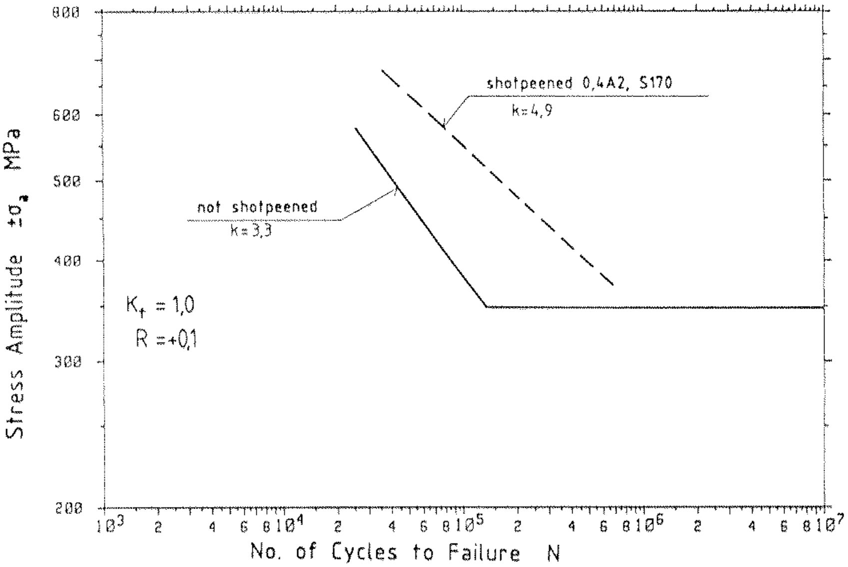


Fig. 3: SN-Curves for Unnotched Specimens

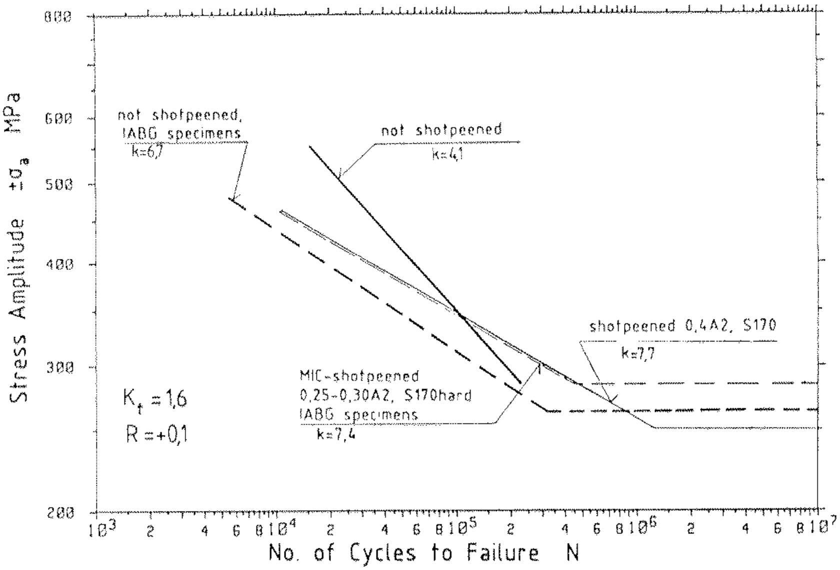


Fig. 4: SN-Curves for Notched Specimens

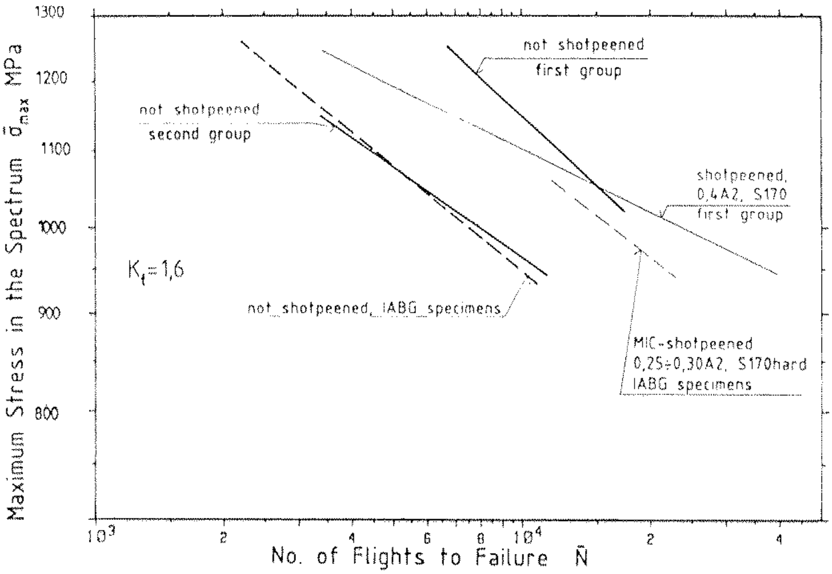


Fig. 5: Fatigue Life Lines for the Flight by Flight (FALSTAFF) Tests

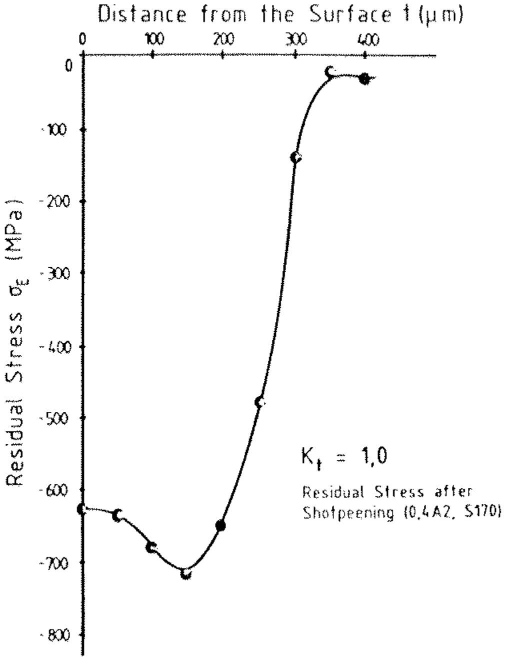


Fig. 6: Residual Stresses Distribution