An investigation into the influence on the fatigue strength of aluminium alloy parts of load spectrum base level and residual stresses induced by shot peening or straightening

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In this investigation of high-strength aluminium plate material, the influence of total surface stress in the short transverse direction on the fatigue life has been studied. The total stress was composed of surface residual stress and stress due to spectrum loading of the U-shaped specimens used. A number of residual stress levels and -distributions were obtained by different combinations of shot peening, with and without preload, and static overloading. In addition, three levels of testing base stress were used.

The fatigue test results indicate that the total surface stress generally is the decisive parameter in the case of short transverse loading and thus should be used in cumulative damage calculation. When shot peening was applied as the last specimen preparation step, however, fatigue crack initiation tended to take place well below the critical surface. In this case, shorter-than-calculated fatigue lives were obtained.

Introduction

High-strength aluminium alloy plate is widely used in today's aircraft industry for manufacturing structural parts. Contributing to its popularity has been the access to highly efficient, numerically controlled milling-machines, which can easily transform a thick piece of plate into an intricately shaped, 3-dimensional part. In many cases, though, more than 95 percent of the material ends up as chips as a result of this process.

With this design philosophy, it is often unavoidable to subject the material to high static and dynamic stresses in its weakest - short transverse - direction. One possible means of enhancing the short transverse fatigue properties of the finished part is shot peening. The investigation to be described in this paper formed part of an over-all assessment of cost versus benefit associated with the use of shot peening.

Experimental details

Plate in aluminium alloy AA7050-T73651 was used in this investigation. The yield and tensile strength in the short transverse (ST) direction of the plate were 420 MPa and 490 MPa, respectively.

U-shaped specimens (Fig. 1) were machined from the 80 mm thick plate. The curved surface, which was machined in the tangential direction by milling, leads to a stress concentration $K_t = 1.23$ in the critical section, i.e. at the midplane of the plate thickness. The load is transferred into the specimen by fork connections and steel bolts. Due to the great specimen thickness, the centre of the test surface experiences a biaxial stress state. (In the following text, however, only stresses in the loading direction, z, will be mentioned).

The fatigue testing was performed in two load frames with closed loop-controlled servohydraulic actuators. A load spectrum for the wing root area of a fighter-type aircraft was used, the maximum load of which 23.5 kN corresponds to the extreme surface stresses of 380 MPa and -100 MPa in the critical section of the specimen.

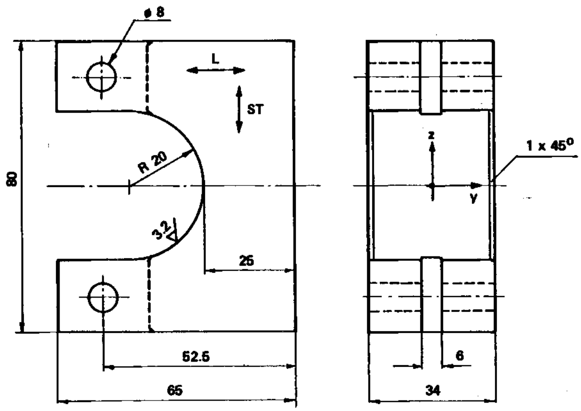

Fig. 1: U-shaped specimen. Material AA7050-T73651.
The coordinates y/z in test surface will be used through out the paper. Loading is in z-direction.

A number of base surface stress levels during fatigue testing were achieved by different pre-treatments of specimens, causing surface residual stresses to develop, and by application of a static base load level at testing. The pre-treatments were either shot peening, shot peening of the preloaded specimen or overloading the specimen:

- Shot peening was carried out on the curved surface and to some extent on the surrounding surfaces. The peening was done with S230 steel shot ($d_{mean} \sim 0.6$ mm) to an Almen A intensity of 0.20 mm and 150 % coverage.
- Shot peening was carried out on specimens that were kept under preload, either in tension +9.5 kN or in compression -9.5 kN, which corresponds to surface stresses ± 150 MPa in the critical section.
- Overloading, as simulation of a straightening operation, was carried out on shot peened specimens and on (virgin) specimens that were to be shot peened afterwards. The compression loading to -40 kN, at the temperature 140°C, caused plastic deformation of the surface regions.

In addition to the treatments mentioned, some virgin (as-milled) specimens were tested and also specimens that had been anodized in cromic acid. By adding different base load levels at testing, altogether 10 series were tested. The 10 "test cases" are displayed together with the fatigue results in the next section, Fig. 2.

Fatigue results

The spectrum fatigue results are shown in Fig. 2 as 'Number of flights'. Four specimens from each series (two from series Nos. 8 and 10) were tested, all at the spectrum reference load 23.5 kN. At ~10^5 flights a test was terminated.

Series No. 1 with as-milled specimen is taken as a reference. Series No. 2 shows that anodizing reduces life to 50 %. According to series Nos. 3 and 4 shot peening increases life to > 200 %, notably even with anodizing as final treatment. Series No. 5 shows that compressive overloading after shot peening is strongly deteriorating. Series No. 6 indicates that overloading which is followed by shot peening has no critical influence. Series Nos. 7-10 show that a static base load level has a strong effect on fatigue life.

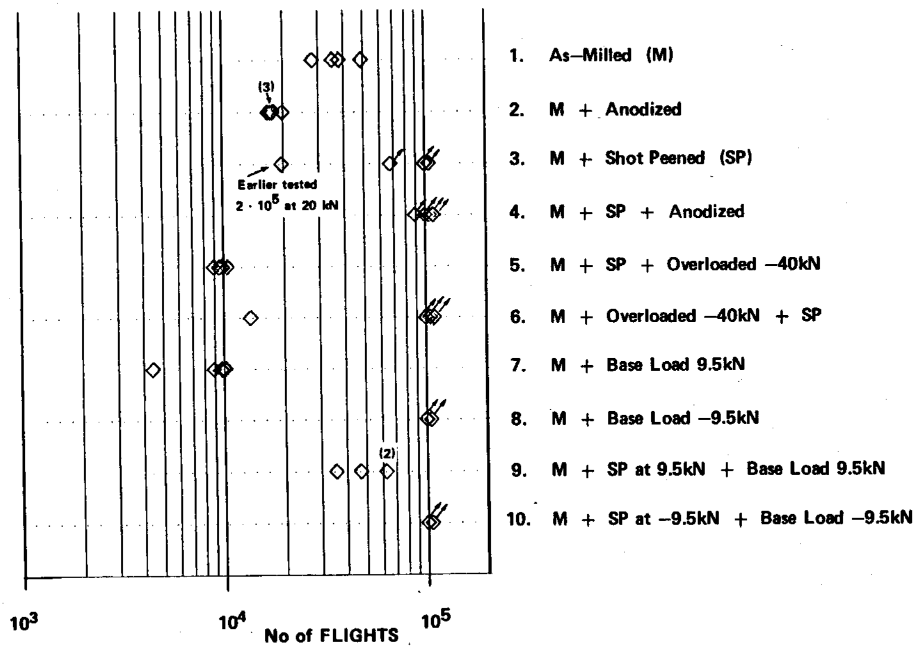

Fig. 2: Spectrum fatigue results of specimens with various surface treatments and/or base load conditions. Spectrum reference load 23.5 kN.

Fracture characterization

Series No. 1 - milled surface only - is taken as a starting-point. Fatigue fracture has initiated at the chamfered edges in almost all cases. Spectrum loading with a positive base load (series No. 7) gives rise to several initiation points, none of them situated at an edge. The same is true for series No. 5 (shot peened, then overloaded in compression).

In specimens belonging to series No. 2 the brittle nature of the oxide surface layer has caused crack initiation to take place in several different, parallel planes. After some of them have grown and joined up, a characteristically stepped crack profile is obtained (Fig. 3).

In three of these test series, one specimen - with the shortest or second shortest fatigue life - exhibited fracture initiation at a point well below the surface. In three of the remaining series (Nos. 3, 6, 9), with shot peening as the last operation, all fatigue failures started in this way. Evidently these spots, forming bulls-eyes (Fig. 4) represent weak points, to the extent that initiation could take place up to 2 mm below the surface.

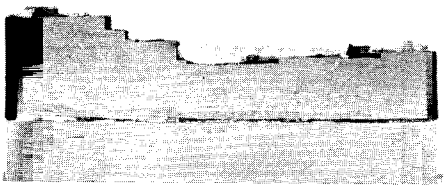

Fig. 3: Stepped crack profile of anodized specimen.

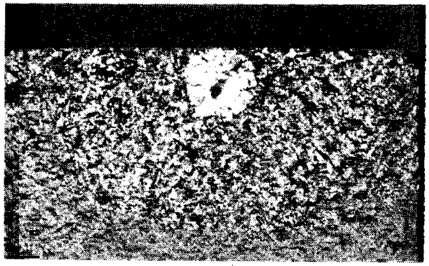

Fig. 4: Sub-surface crack initiation.

Residual stress measurements

The distribution of residual stress σ_z below the curved surface was recorded in four cases: normal shot peening, shot peening under tensile and compressive preload and shot peening plus compressive overload. In the first three cases, stress measurements - by the x-ray diffraction, $\sin^2 \Psi$ method - were made step-by-step after electropolishing. In the second case (tensile preload), however, only a broken specimen was available for this investigation, and so the measurement had to be made ~5 mm off-centre. - Correction for the influence of stress gradient was applied.

The long-range stress distribution of the shot peened and overloaded specimen was measured on one of the surfaces exposed by making a midplane cross-section (xz-plane). No attempt was made to compensate for the effects of disturbing the stress balance.

The stress distributions produced by shot peening with and without preload are shown in Fig. 5. From an earlier work [1] it is known, that a tensile preload increases the stress magnitude and the depth of penetration, whereas a compressive preload works in the opposite direction. Here, however, the difference between curves b and c (zero and tensile preload) is small, mainly because the measurements were made at a distance from the plane of symmetry in case c. Considering also earlier measurement results, a surface stress value of -300 MPa will be used in the calculation of the fatigue life of specimens shot peened under tensile preload.

For as-milled specimens, an average surface residual stress value of -50 MPa was calculated from four measurements.

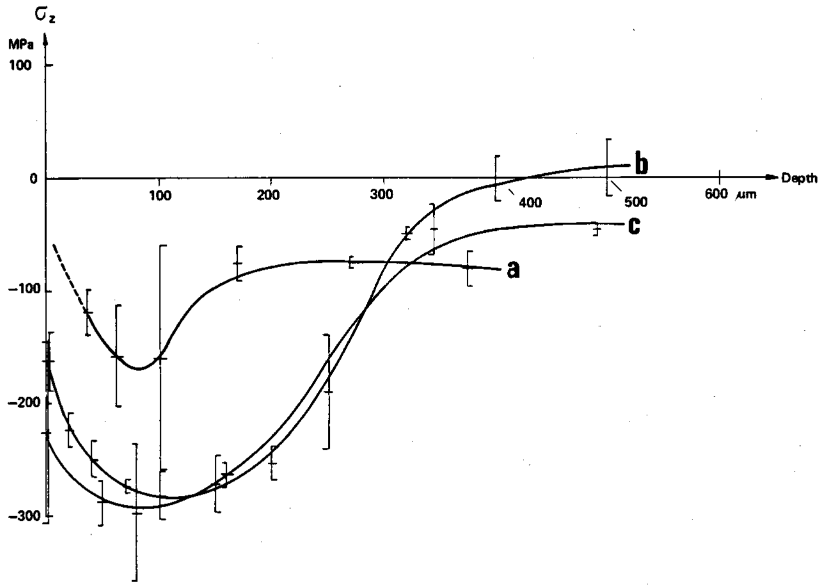

Fig. 5: Distributions of residual stress σ_z achieved by shot peening under preloads -9.5 kN (a), 0 kN (b) and 9.5 kN (c), respectively. (9.5 kN corresponds to a surface stress of 150 MPa).

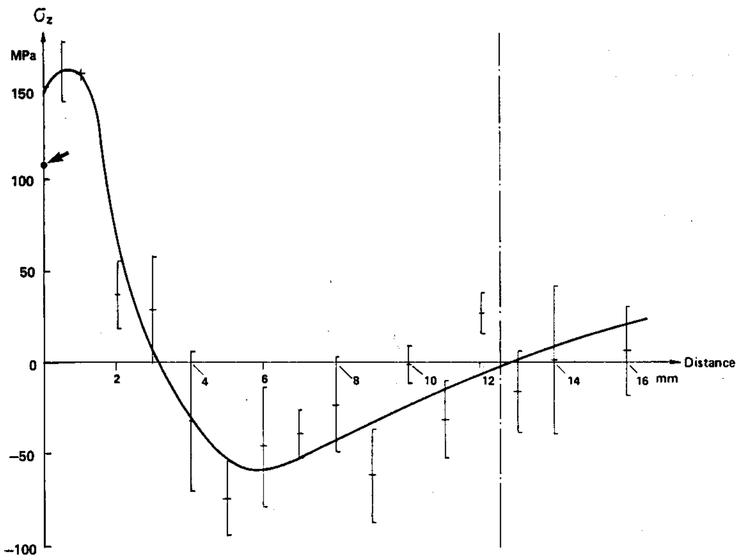

Fig. 6: Longe-range residual stress distribution (σ_z) of shot peened and overloaded specimen.

Fig 6 displays how the z-direction residual stress varies with distance from the curved surface of the shot peened and overloaded specimen. Sectioning the specimen has released the y-component of residual stress, which explains the increase in surface stress σ_z from the value measured at the surface before sectioning (arrow). This latter value (110 MPa) will be used in the cumulative damage calculation (next section).

Cumulative damage calculation based on total surface stress

An approach to the study of the correlation between the total surface stress level and the fatigue life was made by assuming simple superposition of known stress values. That includes measured surface residual stress values (previous section), stress due to base load at testing and the maximum (and minimum) stress caused by the spectrum load. This is schematically shown in Fig. 7.

The base surface stresses for different series achieved in this way were used as input data in a linear cumulative damage calculation based on axial fatigue data for the ST-direction of the plate material used. The actual load spectrum was used in the calculation. The calculated fatigue lives, i.e. when the damage sum equals one, are given in Table 1 together with the experimental fatigue lives.

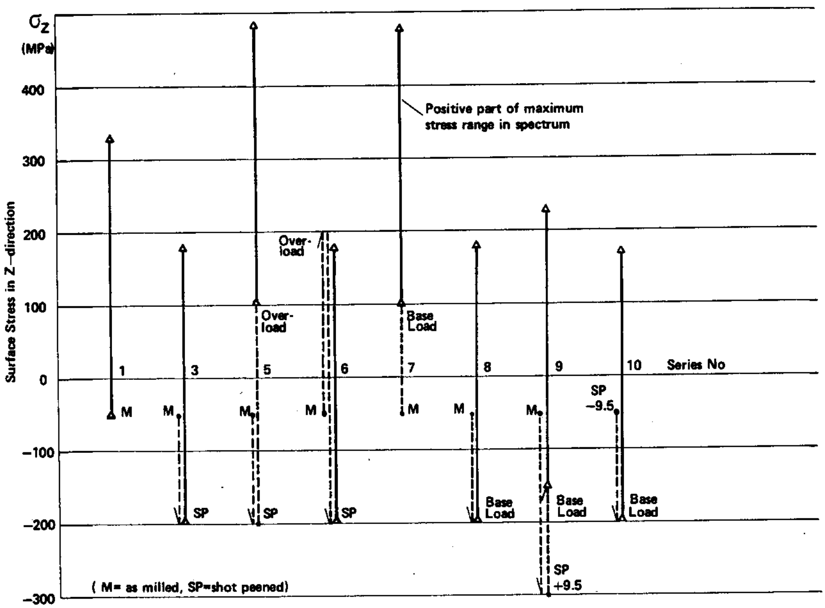

Fig 7: Addition of surface residual stress and stresses due to base load and maximum stress range in spectrum

Series No.	"Test case"	Base level of surface stress (MPa)	Fatigue life	
			Calculated	Experimental
3 6 8 10	M + SP M + Overloaded-40kN + SP M + Baseload-9.5kN M + SPat-9.5kN +BaseLoad-9.5kN	-200	$5 \cdot 10^5$	$>10^5$
9	M + SPat+9.5kN +BaseLoad+9.5kN	-150	$1.8 \cdot 10^5$	$5.0 \cdot 10^4$
1	M	-50	$3.4 . 10^4$	$3.7 \cdot 10^4$
7	M + BaseLoad+9.5kN	+100	$0.81 \cdot 10^4$	$0.90 \cdot 10^4$
5	M + SP + Overloaded-40kN	+110	$0.74 \cdot 10^4$	$0.95 \cdot 10^4$

Table 1 Calculated fatigue lives as a function of base level of surface stress (due to residual stress and base load) in comparison with experimental fatigue lives.

Discussion

Simple addition of the surface residual stress and the stress caused by the base load at testing is a logical starting-point in an attempt to consider numerically the influence on the fatigue life of a certain residual stress state, since the crack initiation in most cases takes place in or close to the surface. (That shot peening-induced residual stresses in this type of aluminium alloy do not relax during stress cycling with a tension-dominated load spectrum has been found earlier [2], and was confirmed by spot checks in this investigation).

The results of cumulative damage calculation tell us that this straight-forward approach was indeed viable. This fact, and the circumstance that only stresses in the loading direction had to be considered, can both be explained by the fact that the shear-type fatigue mechanisms (initiation and stage I propagation according to [3]) are suppressed in a case when the material is cyclically stressed in its short-transverse direction [4]. The tensile stress-controlled stage II propagation is only influenced by the residual stress component that is parallel with the loading direction.

At first sight it may seem astonishing, that the stress superposition principle gives a good correlation with the total fatigue life also in test series No. 5 (shot peening plus compressive overload), where the tensile residual stress of the specimen surface zone sharply decreases with depth and, within 3 mm from the surface, turns into a compressive stress. This is explained, however, by the fact that the stress intensity of the fatigue crack increases with $(\text{depth})^2$, which more than compensates the decrease in the crack-propagating total stress.

In those cases when the residual stress variation with depth is a mirror-image of the one just described, i.e. when shot peening was the final preparation step, there is a tendency that crack initiation takes place at a considerable depth below the surface. (This is true also when the outermost surface zone consists of a crack-prone, brittle oxide layer as in test series No. 4). In the extreme case - shot peening under tensile preload - this different mechanism is reflected in shorter-than-calculated fatigue lives. - The variability in crack initiation depth and the appearance of the crack initiation area seem to be characteristic of fatigue loading of aluminium alloy specimens in the short transverse direction. This topic deserves further study.

Conclusions

This investigation of the short transverse fatigue properties of high-strength aluminium alloy material has shown that

- normal shot peening increases the fatigue life (at the chosen spectrum reference load) by more than 100 percent

- this result, and the effects of shot peening under preload, as well as shot peening in combination with static overloading, could be rationalized by cumulative fatigue damage calculation, using the surface residual stress as a corresponding testing base stress

- in the case of "reinforced shot peening", i.e. shot peening under tensile preload, fatigue crack initiation was displaced inwards from the surface. The experimental fatigue lives were shorter than calculated here.

References

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(2) B. Jaensson: Fatigue - Fundamental and Applied Aspects, Rimforsa, Sweden, 15-18 August 1977.

(3) W.J. Plumbridge, D.A.Ryder: Metallurgical Reviews, Review 136, 1969.

(4) B Jaensson: Swedish Symposium on Residual Stress, Sunne, Sweden, 30 March - 2 April, 1987.