THE CONTROL AND USE OF RESIDUAL STRESSES IN AIRCRAFT STRUCTURAL PARTS

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1. Introduction

The phenomenon residual stresses is sometimes loosely referred to as the probable (contributary) cause of otherwise unexplicable fatigue failures of aircraft structural parts. Based upon the authors' combined experience in the fields fatigue testing - design - residual stress measurement, mainly on 7000-type high-strength aluminium alloys, this overview paper is intended to help the designer to avoid unwanted residual stresses with its negative consequences, and also to explain how intentionally achieved residual stresses can be utilized to improve the fatigue resistance of structural parts.

Several aspects of "residual stresses" will be touched upon in the paper:

- how they arise, how they can be controlled and how they interact with cyclic deformation phenomena

- deliberately introduced, induced by service loads, or occurring as a by-product of heat treatment or straightening.

2. Origin of residual stresses

Two schematic examples will be given of the origin of residual stresses. In the first case it will be described qualitatively how a solution heat treatment gives rise to a long-range stress distribution in a cylinder of a material which does not undergo phase transformations [1].

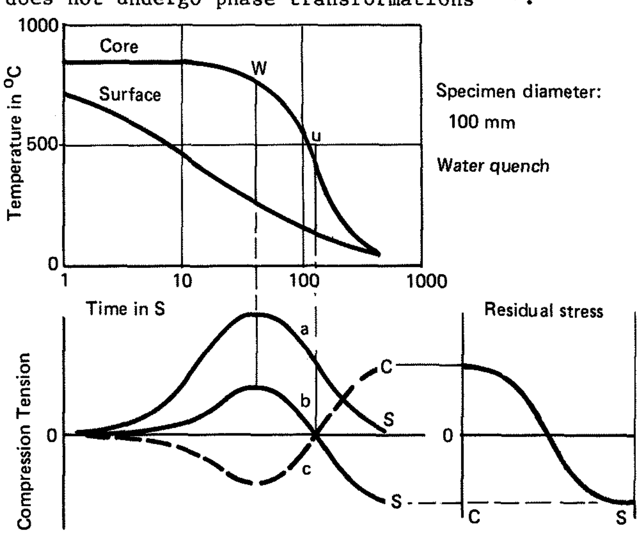

Fig 1 Origin of thermal residual stresses during quenching [1].

Fig 1 shows cooling curves for surface and core material during quenching from a high temperature. Initially, the surface cools more rapidly than the core. Gradually, the increasing difference in thermal contraction causes the case material to stretch out by plastic flow. At a later stage the cooling curves start approaching each other again, which means that the core material shrinks faster than the surface zone. The transient stress distribution is gradually reversed, due to the earlier material redistribution, and the tendency to high compressive residual stresses in the outer region is enhanced by the fact that the flow stress of the material increases with decreasing temperature. The final result is a residual stress distribution of the type shown in the right diagram of Fig 1.

Elaborate quantitative treatments of the subject heat treatment - residual stresses in materials with and without phase transformations have been presented at a symposium in Linköping in 1984 [2].

Next let us try to visualize what happens in the outer zone of a metal part being bombarded with hard "balls", i.e. during shot peening or peen forming (Fig 2).

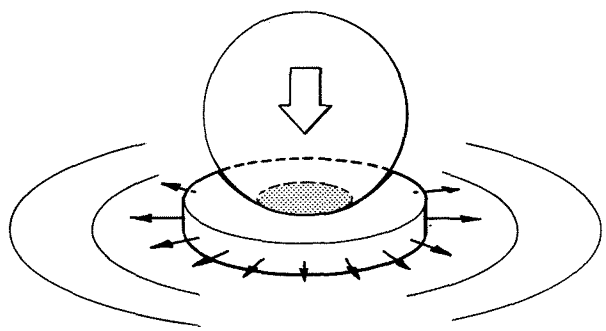

Fig 2 Impingement of a steel shot on the surface of an elastic-plastic material

The impingement of each ball makes a circular disc of metal flatten, forcing the next surrounding annulus to increase in size plastically against the elastic constraint of the material outside this annulus. The result is a circular symmetrical field of compressive residual stress. By the action of consecutive impingements, more or less overlapping the first one, the residual stress field spreads over the bombarded surface.

In the case of a "normal" relationsship between the hardness levels of shot and target, respectively, the highest compressive stress occurs at a certain depth below the surface, around the level of the maximum resolved shear stress. With increasing depth the magnitude of the residual stress is reduced and it changes sign to a zone of balancing tensile stresses.

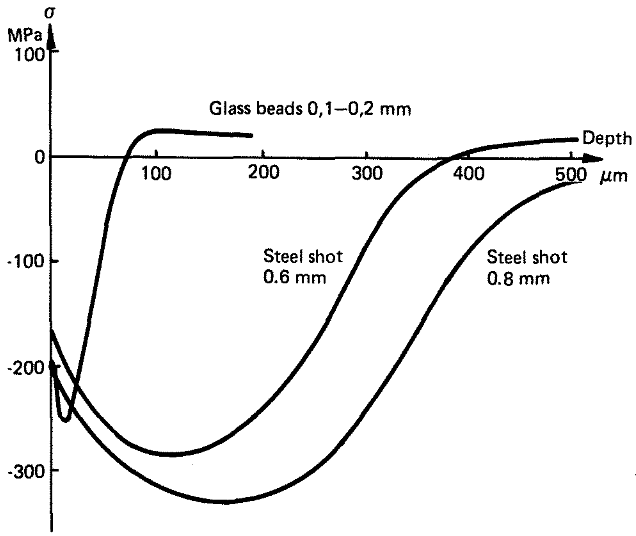

Fig 3 Residual stress distributions achieved by peening with steel shot or glass beads.

Fig 3 shows residual stress distributions obtained in a 7075-type aluminium alloy by shot peening with cast steel shot of two different size ranges, with mean diameters 0.6 and 0.8 mm, respectively. The third stress distribution is a result of glass bead peening. In this case, the nominal glass bead size interval was 105-210 μm.

3. Consequences of heat treatment residual stresses

In the first of these two examples the residual stresses are an unavoidable by-product of the heat treatment process. The stress field extends right through the part. In the second case a shallow layer of material is deliberately achieved, characterized by compressive residual stresses and a high dislocation density (cold work).

Heat treatment residual stresses, occurring in semi-finished products like hand forgings, die forgings or plate, have a negative influence on the chip-cutting process used to transform it to a final machine or vehicle part. This kind of stresses (called first order residual stresses) form a balanced stress state through the article. Removing material frome one side disturbs the stress balance and the part tends to distort, against the restraining forces of the clamping. The aim of achieving close dimensional tolerances requires a time-consuming procedure to be used: rough machining from side 1, the same from side 2, final machining from side 1, final machining from side 2. Still more steps may be required in difficult cases.

Technically the most serious consequence of residual stresses in the semi-finished product is that, in spite of all efforts, the machined part in some cases exceeds the given tolerances, necessitating a straigthening operation to be carried out. By straigthening, a new balanced state of residual, tensile and compressive, stresses is set up. The magnitude and distribution of these stresses are difficult to predict; very high stresses will arise locally, depending upon the part's geometry.

Designing an aircraft structural part to be machined from a conventional die forging implies that two thirds to three fourths of the forging will be transformed to chips. Although, by this operation, the original residual stress distributions are smoothed out to a large extent, remnants of them may prove detrimental to the part's fatigue behaviour.

The basic characteristic of the residual stress distribution of a semi-finished product which, during quenching, has not undergone a phase transformation, is that compressive stresses in an outer zone are compensated by tensile stresses in the interior. (Strictly speaking: compressive stresses in the first cooled material, tensile stresses in the last cooled material). After the stress redistribution which takes place when the outer material layers are removed, this will normally still be true in the case of a simple geometry and more or less equal thickness all around of the material removed.

However, in a typical aircraft spar or frame design, consisting of webs, flanges and stiffeners (Fig 4), the die forging with its draft angles has a much more rounded shape than the part to be machined from it. This means that inner corners of the final contour in some areas will be situated so far below the surface of the forging that there will be residual tensile stresses (parallel to the flange) exposed at the final surface.

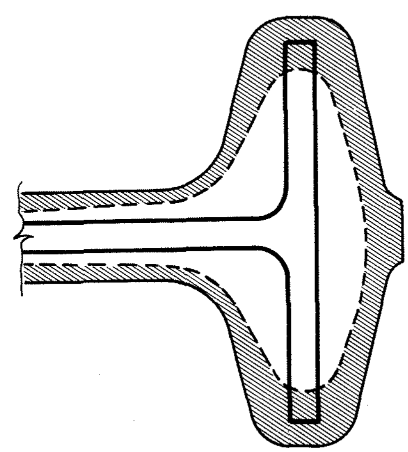

Fig 4 Cross-section of a die forging. The contours of the machined part are shown, as well as the assumed boundary between compressive and tensile residual stresses before milling.

An example of this was found once when a residual stress investigation was carried out in search of the reason why fatigue cracks started in an unexpected area of a wing attachment frame member. During fatigue testing of the frame, cracks initiated in the transition zone web - outer flange of the part (Fig 5), which had been machined from a die forging.

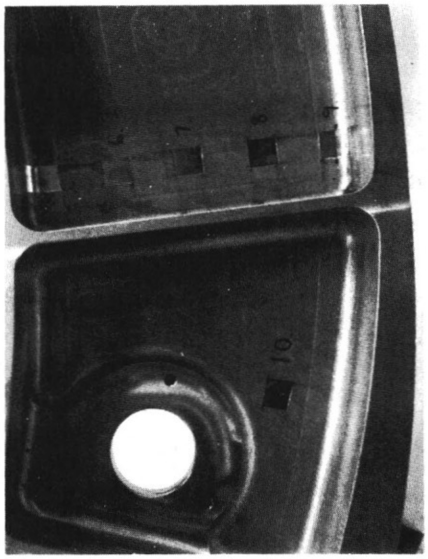

Fig 5 Detail of wing attachment frame. Locations of residual stress measurement are indicated.

Fig 6 shows the pattern of tangential residual stresses found: tensile stresses close to the flanges, compressive stresses in the centre of the web. - The final weakening effect, which provoked fatigue crack initiation, was a threaded bottom-hole, erroneously penetrating the flange in the fillet radius.

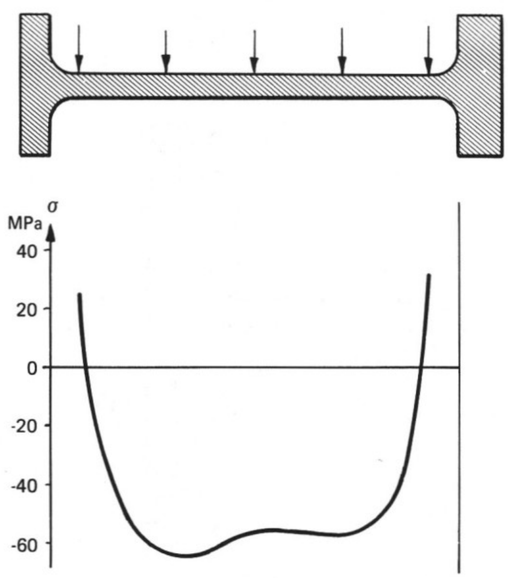

Fig 6 Tangential residual stresses measured on wing attachment frame part.

4. Stress relieving of die forgings

Heat treatment residual stresses can be minimized by the use of a slower cooling from the solution treatment temperature. In the case of thick sections, however, this could mean a conflict with the requirement for through-hardening, and one must resort to mechanial stress-relieving methods, applied between solution treatment and ageing.
Most efficient is stretching, which is used with extrusions, plate and long hand forgings. Die forgings are "cold compressed" or "coined", either by means of the finishing forging dies or a special set of dies.

The term "cold compression" is somewhat misleading, since the major effect also in this case is stretching. It is accomplished by the wedging action of the die against the draft angles of flanges and stiffeners (Fig 7). Design elements of this kind are essential for an efficient stress-relieving treatment, together with the difference in lateral dimensions between die and work-piece, normally brought about by the difference in thermal contraction from the forging temperature between the steel die and the aluminium work-piece.

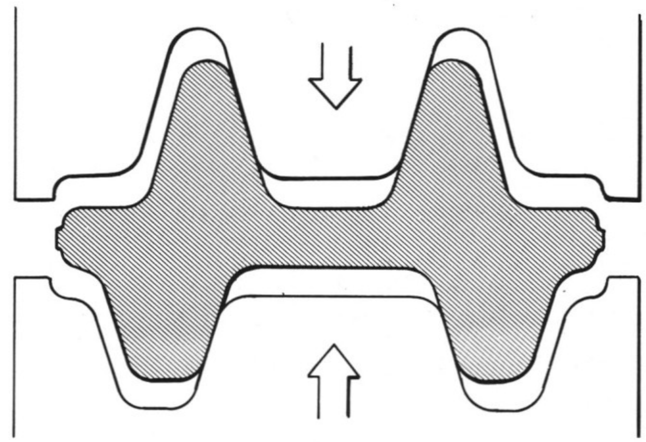

Fig 7 Cross-section of a forging being cold compressed in the forging tool.

A refined variant of the cold compression method has recently been evaluated at Saab-Scania, using a combination of residual stress measurement and machining trials.

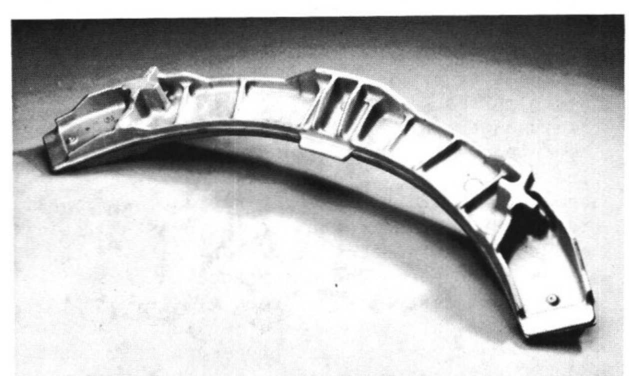

Fig 8 Fuselage frame forging

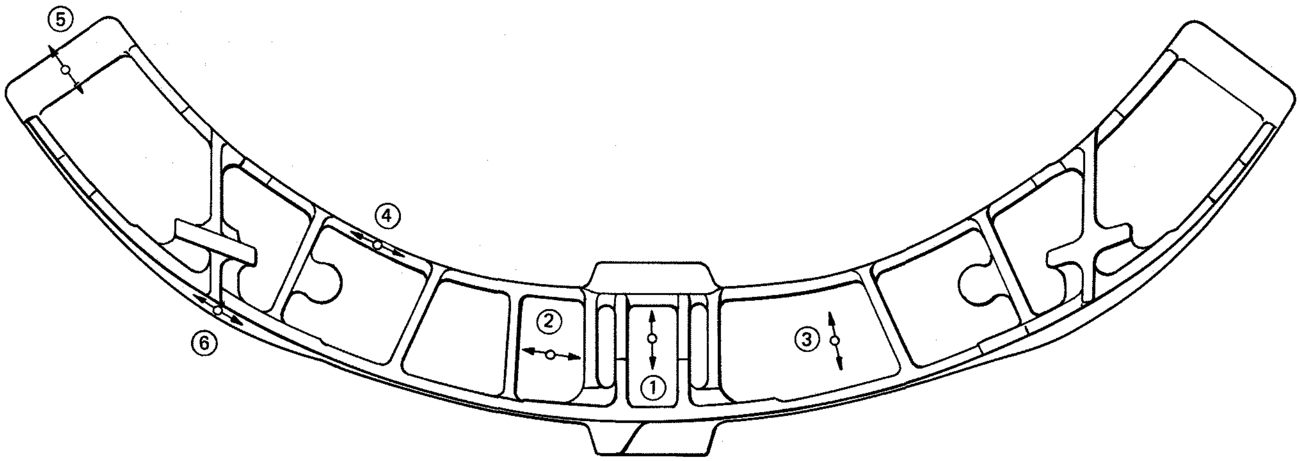

Fig 9 Drawing of fuselage frame forging. Locations of residual stress measurement are indicated.

For this investigation a fuselage frame forging, weighing 27 kgs, with flanges and stiffeners on both sides was chosen (Fig 8). Four forgings of each kind were made in aluminium alloy AA 7010, with and without cold compression. At five locations (Fig 9), the residual stress variation with depth below the surface was measured, using the following method:

- surface stress measurement
- milling a narrow slot in the direction of the measured stress
- chemical removal of the surface layer cold-worked by milling
- stress measurement in the bottom of the slot
- further milling, etching, stress measurement etc.

Removal of material affects the stress state, leading to "false" stress values. The effect is small, however, and not even of academic interest in a comparative investigation. Also, from a practical point of view the method is nondestructive as long as the milling of slots is restricted to material volumes which will be removed during the machining operation.

Two examples of the measured stress distributions will be given. The first diagram (Fig 10) shows the variation of residual stress (in the tangential direction) with depth down to 31 mm below the surface at location No 6 - in the outer flange. The magnitude of residual stresses, either compressive or tensile, has been greatly reduced by the cold compression treatment.

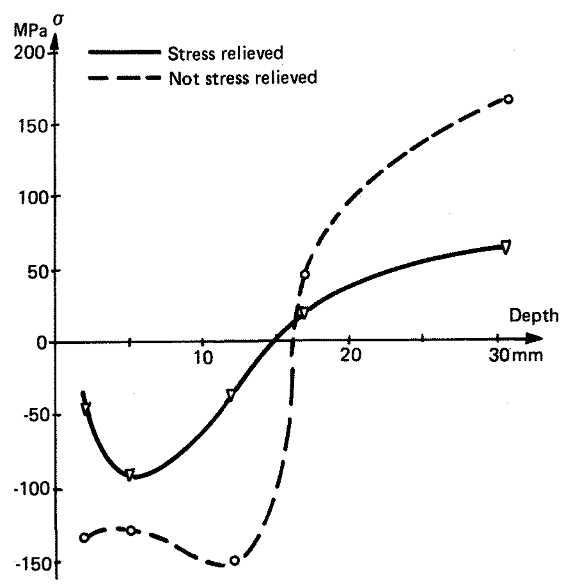

Fig 10 Residual stress distributions in outer flange (location No 6).

The next diagram (Fig 11) shows transverse stresses in a web section (location No 3). Surprisingly, in this case the magnitude of the residual stresses is greater in the cold-compressed forgings than in those which had not been treated. The tendency is the same at the two other web locations investigated: high compressive stresses in the surface, sharply decreasing with depth in the non-compressed forgings, less so in the other case or even increasing in magnitude.

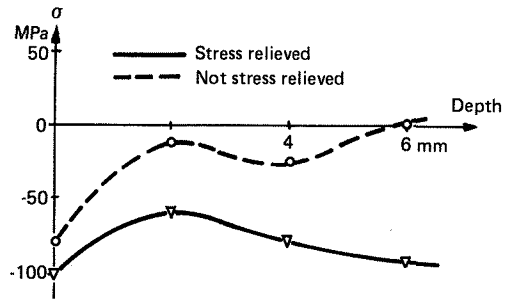

Fig 11 Residual stress distributions in web section (location No 3).

This rather unexpected result of cold compression can be explained in the following way.

Consider a "spar element" consisting of a single web area surrounded by a rectangular frame (Fig 12). In each direction, the web material is efficiently stretched by the tool acting on the respective part of the frame, at 90° angle to this direction (elements 2-6). The parallel frame parts, however (elements 1 and 7), are affected only via shear forces near the corners, and are left virtually un-strained. The total result is, that the web material is kept under biaxial compressive stress by the surrounding frame. - In a real spar, consisting of several elements in a row, the greater part of the flanges will be stretched out as a results of "cold compression", but the transverse stiffeners will still keep the web portions under compression.

Machining of three plus three forgings was done in a numerically controlled milling-machine, following the normally used sequence of operations: rough milling, side 1 and side 2, finish milling, side 1 and side 2. After each step the geometrical position of a large number of points on the forging's surface was measured, to give the displacements - normal to and in the plane of the article - between the two rough milling operations as well as between the two finish milling cuts.

Fig 13 shows graphically the displacement - normal to the forging's plane - of each measurement point between the two rough milling operations. For each group of forgings, stress relieved and non-stress relieved, averages of absolute values are given. Obviously, the stress-relieving operation has dramatically reduced the forging's tendency to move perpendicular to its plane.

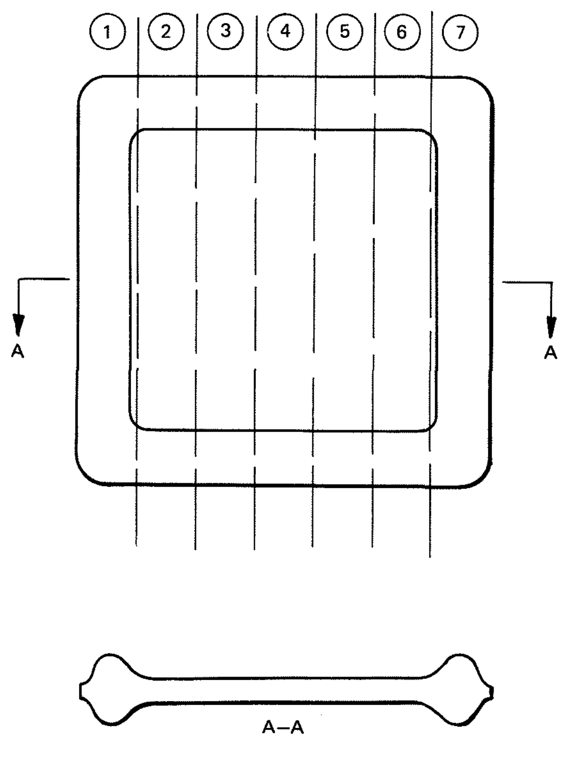

Fig 12 Hypothetical "spar element".

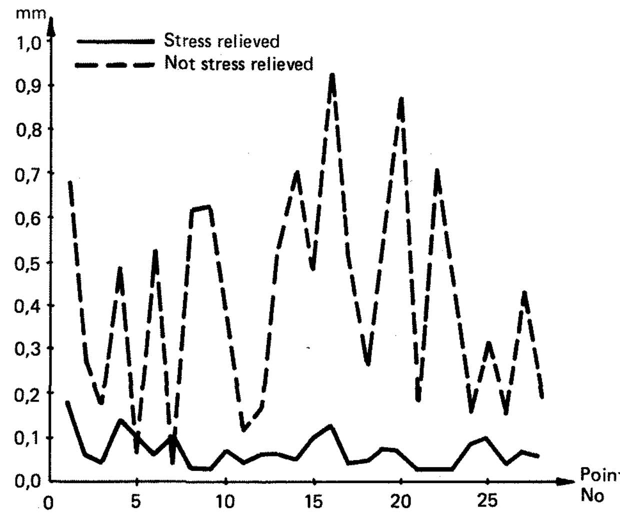

Fig 13 Displacement of measurement points normal to the plane of the forging between two rough milling operations.

What concerns distortion in the plane of the article, the effect is noticeable but much smaller (Fig 14). The distortion behaviour confirms the over-all picture obtained from the residual stress measurement: the major effect of the stress relieving operation is a reduction of the through-thickness stress gradients.

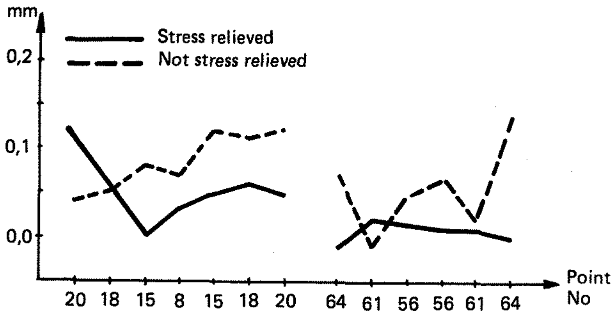

Fig 14 Displacement of measurement points in the plane of the forging between two rough milling operations.

5. Load induced residual stresses

Load induced residual stresses form another group of related problems. They can be found in metallic material parts with non interference fit bolt holes or other notches, in cases where high loads sometimes are present either in tension or compression.

It is a bad case, when high compressive loads in a nominally harmless spectrum induce residual tensile stresses by locally exceeding the compressive yield limit. Isolated tensile stresses of this kind can shorten the fatigue life and the effect will be especially severe, if these high compressive loads are repeated a number of times during the service or test period.

Some cracks which were apparently connected with load induced residual stresses were found at the full scale fatigue test of the Saab Viggen aircraft in its attack version. The circumstances were as follows.

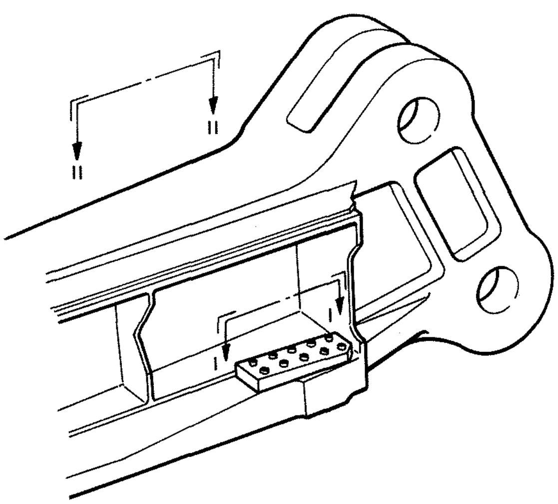

Fig 15 Test areas of wing spar.

The upper part of the main wing spar (Fig 15) was extensively loaded in compression. The flanges had loose fitting bolt holes for joining the upper wing panels (Fig 16). The area is located just outside the forked lug joint (view II-II in Fig 15).

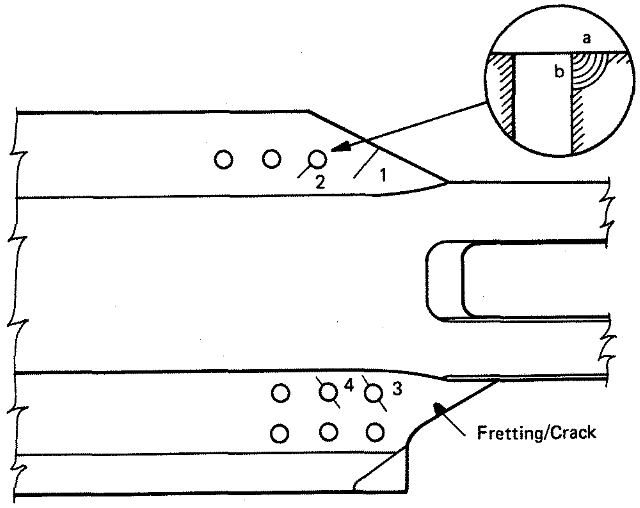

Fig 16 Cracks in the upper compression part of the wing spar.

The spar was made of a die forging in the aluminium alloy AA 7009 with R_m = 480 MPa and R_{p02} = 420 MPa. The hole diameters (for steel bolts) were 8 or 10 mm and the thicknesses of honeycomb panels and spar flanges were 15 and 11-14 mm, respectively.

The load spectrum with its dominating compressive loads is shown in Fig 17. S_{GL} denotes the nominal limit load stress.

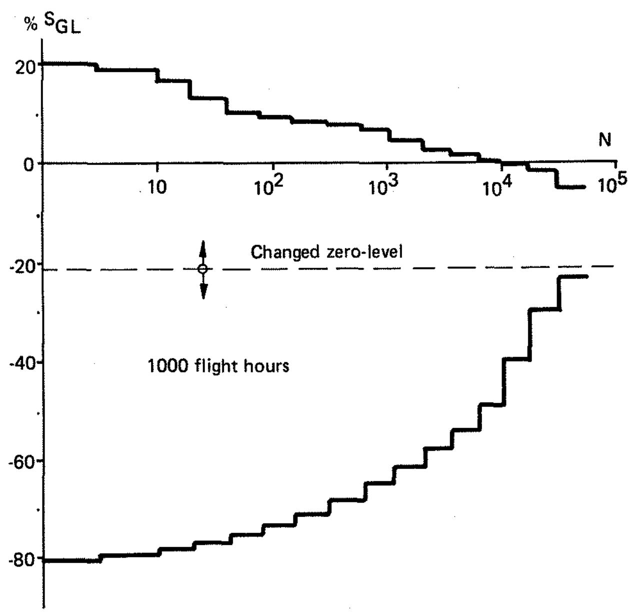

Fig 17 Load spectrum.

The primary problems with the wing spar of the Viggen aircraft were related to the lower rear flange (I-I in Fig 15). One important goal for the full scale fatigue test was to verify solutions of these problems [3]. The left and right hand wing spars were therefore slightly different on the tension side, but the upper compression parts were equal.

The edge type crack denoted 1 in the upper forward flange in Fig 16 and the fretting fatigue crack in the rear flange were found only in the left wing spar. Corner cracks at bolt holes denoted 2, 3 and 4 in Fig 16, however, developed in both the left and right spars. Therefore they must be looked upon as significant phenomena for the design, stress level and spectrum. These corner cracks are the subject of a short analysis.

The first cracks were seen at hole No 4 of the left spar after 2 800 h test simulated service time (a x b ≈ 2 x 2 mm). After 5 600 h NDE inspectors found cracks at holes No 2 and 3 of the left spar and the first crack of the right spar at hole No 4. After 9 100 h the right spar had got cracks also at holes No 2 and 3. The corner cracks propagated slowly and the first fixes were introduced at 13 000 and 14 000 h, when required factored service time had been exceeded with good margins. The test was continued to 16 800 h, the last 2 800 hours of which at 15 % increased load level.

Stress measurements were made using strain gauges and X-ray camera to determine global reference stresses and local residual stresses, respectively, after material at positions 1 and 2 in the left spar had been removed at about 13 000 h by a radical milling operation to eliminate large cracks. The local stress situation at holes with more normal corner cracks was not experimentally traced, however.

Various theories to explain the appearance of the cracks were discussed. Regarding the fatigue cracks at bolt holes they were finally considered to be the result of residual tensile stresses induced by the high compressive loads of the spectrum.

At or in collaboration with Saab's stress department for military aircraft appropriate calculation methods have been developed for determination of residual stresses emanating from cyclic loading [4, 5]. Neuber-rule theories as well as more general methods have been studied.

Consideration to residual stresses was introduced in the Saab computer program for cumulative fatigue damage calculation, a program of the Relative Miner type. A set of governing short peak load sequences controls the residual stresses and in that way the fatigue life calculation.
Regarding the case of the Viggen wing spars, cumulative fatigue damage calculation was made under the following premises.

The nominal small test specimen data, forming a Haigh diagram for the fatigue strength, was corrected in two steps:

- to represent lower quartile data
- for size and surface effects

(The total correction represents ~ 20 % lowering of the nominal fatigue strength).

The stress concentration factor K_t was alternatively chosen to 2.5, 3.0 and 3.5 in the calculation. The value 3.0 seems to be the most probable, but it may be increased by secondary effects.

The limit load level S_{GL} was varied in the calculation, the result of which is shown in Fig 18. S_{GL} was approximately -380 MPa in the full scale test. This stress level and the interesting testing times 2 800 h, 5 600 h etc are indicated in Fig 18.

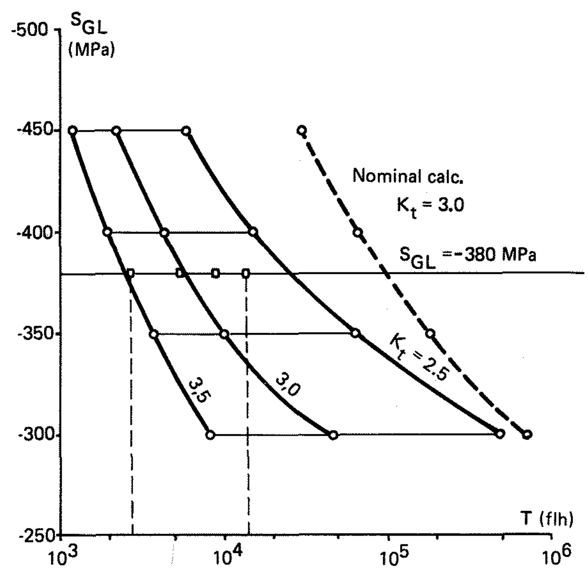

Fig 18 Results of a cumulative damage calculation.

The calculation result, which in a plausible way explains what was found in the full scale fatigue test, is about 15 times more conservative on life basis than a nominal Miner calculation.

The main reason for this is the consideration of a local tensile residual stress of about 240 MPa (at $K_t = 3$) or equivalent to the nominal value $S_{res} \approx + 80$ MPa.

When fixes were introduced in the forward flange of the left spar at 13 000 h, local residual stresses of the above level were in fact measured, but they were not necessarily also representative for the hole edge.

The conclusion is, however, that high spectrum loads in compression can deteriorate the fatigue strength in notched areas by creating residual tensile stresses which move the zero-level of the spectrum to a far more critical position (Fig 17). A consequence of this is that non-interference fit bolt holes should be avoided in highly compression-loaded, fatigue-critical areas.

The result also demonstrates that the used calculation method, still under development, works well.

6. Deliberately introduced residual stresses

Different techniques are available for the deliberate introduction of residual stresses and cold-work in fatigue-critical parts. According to the geometrical dimensions of the affected material volume they can be arranged in groups as follows

- deep-acting, locally confined: hole expansion (e.g. sleeve cold working, "SCW")
- affecting a shallow surface layer, often covering the greater part of the article's surface: shot peening, glass bead peening, grit blasting, surface rolling
- affecting a shallow surface layer, locally confined: "coining" (around holes), roller burnishing

That the hole expansion method is "deep-acting" often means that the tangential compressive stresses (and the cold-worked zone) extend several millimeters from the edge of the hole (Fig 19). In contrast to this, the tangential compressive stresses emanating from roller burnishing are, typically, confined to a one millimeter thick zone (Fig 20). Next to the hole's edge, the residual stress is zero.

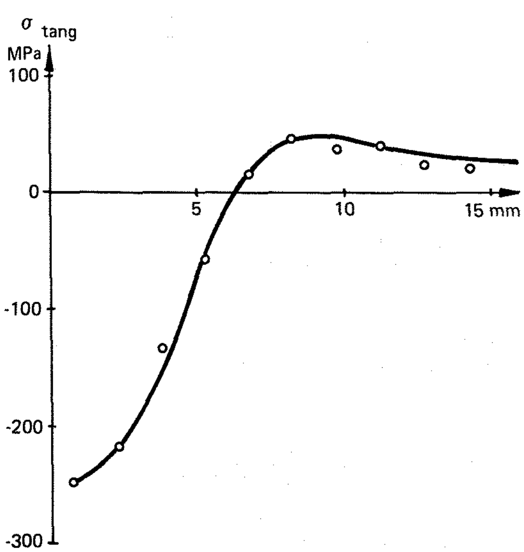

Fig 19 Tangential residual stresses in the vicinity of an expanded hole.

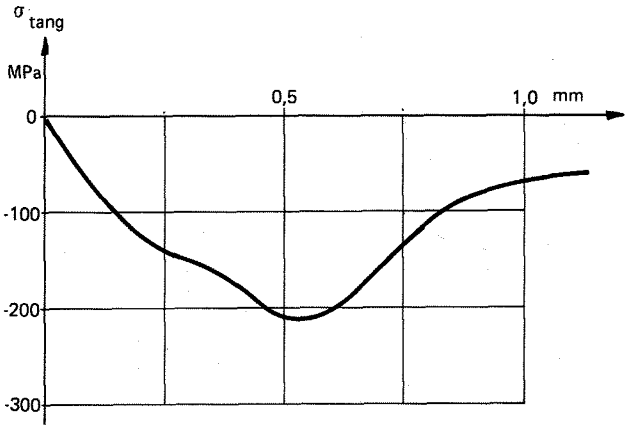

Fig 20 Tangential residual stresses achieved by roller burnishing of a ϕ32 mm hole.

The deep compressive-stress zone around an expanded hole can have a substantial influence upon the design life of the part, not a priori because it will impede a fatigue crack's propagation during a large number of stress cycles, but because it allows the slow-propagation phase to be monitored by inspection.

The second group of stress introduction techniques will be represented by shot-peening. Although it normally has a less enduring and predictable effect on fatigue than hole expansion, shot peening can be prescribed on several different indications, and its mode of action is very complex.

The metallurgically defined initiation and shear-mode progagation phases of a fatigue crack normally extend over the major part of the total fatigue life, although they are geometrically most confined or not even discernible. There is evidence that it is the cold-work effect of shot peening which has the major influence on the initial fatigue crack phases, to the extent that - in the absence of a sharp notch - the initiation takes place under the surface layer affected by peening. The residual stresses _per se_ have an influence only in those cases when the load-induced stress state is clearly bi-axial (6).

When the fatigue process has reached the tensile stress-controlled propagation phase the residual stress component which is perpendicular to the crack acts like a superposed mean stress. The crack will grow only if the algebraic sum of residual stress and load stress at least during part of the stress cycle exceeds zero.

Thus we have reached the conclusion that the plasticizing effect of shot peening influences the first stages of the fatigue process, whereas the accompanying residual stresses are most important during tensile stress-controlled crack propagation. In the case of high-strength aluminium alloys the balance between these two effects is such that shot peening is most useful in those cases when the shear deformation phases are less prominent or are completely missing (7). Reasons for this can be the presence of sharp notches, an inhomogeneous microstructure or the circumstance that the material is cyclically stressed in its weakest direction.

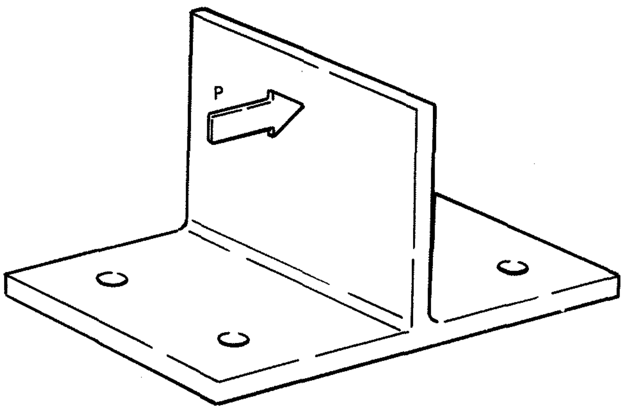

Fig 21 Fatigue specimen with T-shaped cross-section.

Fig 21 illustrates a fatigue investigation where the last-mentioned criterion applies. A fatigue specimen with T-shaped cross-section was subjected to a cyclic bending stress by means of a push-rod acting on the odd member. Four sets of specimens were tested, made from precision forgings or plate, with and without shot peening.

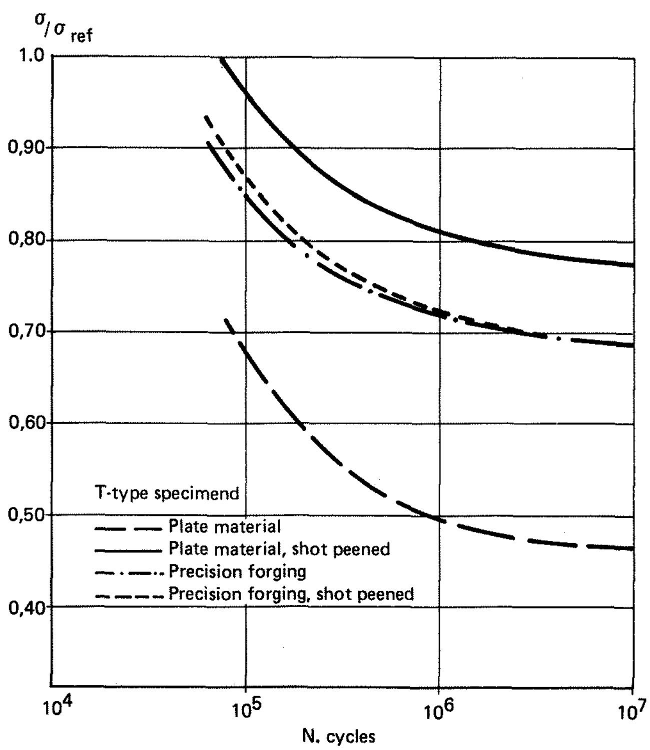

Fig 22 S-N diagram showing results of fatigue testing T-shaped specimens made of precision forgings and plate, respectively.

In the precision forgings the flow lines follow the specimen´s contours exactly. The other kind of specimens were cut out from the plate material in such a way that the odd member of the "T" was at right angles to the grain flow.

It is evident from the S-N diagram in Fig 22 that the fatigue strength of the plate specimens was sharply reduced due to the unfavourable stressing direction relative to the grain flow; the shear-deformation phases of the general fatigue process formed an easily forced threshold here, contrasting to the precision forgings´ behaviour. - Shot peening of the critical zone couldn´t increase the fatigue strength of the precision forgings (Fig 22), but it had a considerable effect in the case of the plate specimens.

This investigation has shown us, that shot peening can eliminate the negative influence of an unfavourable orientation relationship between the material´s grain flow and the applied cyclic stress.

Other cases where shot peening has proven successful is when the part has a brittle conversion coating or a surface coating containing a crack network - it will increase the magnitude of tensile stresses necessary to propagate into the base material cracks which had formed in the coating. Also, the ability of shot peening to displace the fatigue initiation point from the surface means that the outer layer constitutes a kind of protective "skin", thus neutralizing potential crack starters like corrosion pits, tool marks or imperfect fillet radius transitions.

7. Conclusions

Examples have been given of the negative influence of heat treatment residual stresses on the machining behaviour of die forgings and the fatigue properties of structural parts made from such forgings.

A refined stress-relievement process for die forgings has been evaluated by X-ray stress measurement and machining trials. Both methods, the results of which could be correlated, indicate that the treatment is very efficient.

With an example from a full-scale fatigue test it has been shown that high compressive loads in a fatigue spectrum can deteriorate the part´s fatigue properties considerably by creating local, tensile residual stresses in notches. This effect has been successfully considered in a computer program for cumulative fatigue damage calculation.

The stress fields produced by various methods used to intentionally introduce residual stresses and cold-work are characterized. Different situations where these methods should be applied are indicated, based upon an analysis of their effect on different stages of the fatigue process.

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