Control and Use of Residual Stresses in Aircraft Structural Parts

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Examples are given of different kinds of residual stresses, being by-products of heat treatment or deliberately introduced. Typical consequences of heat treatment residual stresses are described, and various stress relief methods are presented. The evaluation of a stress relieving treatment by x-ray stress measurement and machining trials forms the central part of the paper. Residual stresses can also form due to service loading of a structural part. An example of this is described, as well as the rationalization by cumulative damage calculation of the fatigue results obtained. The final section delineates the mode of action of shot peening, which represents a family of fatigue-strengthening cold working treatments. By an application example the possibilities and limitations of such methods are highlighted.

Introduction

THE phenomenon of 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 of fatigue testing, design, and residual stress measurement, primarily on 7000-type high-strength aluminum alloys, this review paper is intended to help the designer avoid unwanted residual stresses with their 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, whether deliberately introduced, induced by service loads, or occurring as a by-product of heat treatment or straightening.

Origin of Residual Stresses

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

Figure 1 shows cooling curves for the 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.

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. The impingement of each ball makes a circular disk 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" relationship 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.

Figure 2 shows residual stress distributions obtained in a 7075-type aluminum alloy by shot peening with cast steel shot of two different size ranges, with mean diameters of 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.

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 semifinished products such as hand forgings, die forgings, or plate, have a negative influence on the chip-cutting process used to transform them to a final machine or vehicle part. These kinds of stresses (called first-order residual stresses) form a balanced stress state through the part. Removing material from 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 use of a time-consuming procedure: rough machining from side 1, the same from side 2, final machining from side 1, and final machining from side 2. Still more steps may be required in difficult cases.

Technically, the most serious consequence of residual stresses in the semifinished product is that, despite all efforts, the machined part in some cases exceeds the given tolerances, necessitating a straigthening operation. Through straigthening, a new balanced state of residual (tensile and compressive) stresses is created. The magnitude and distribution of these stresses are difficult to predict; very high stresses will arise locally, depending upon the geometry of the part.

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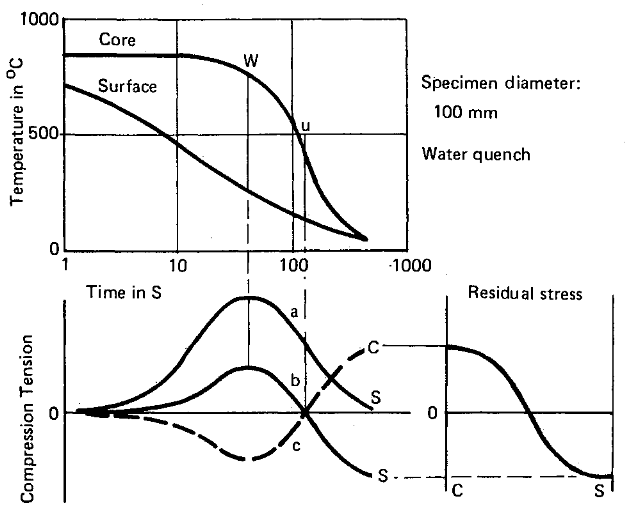

Fig. 1 Origin of thermal residual stresses during quenching.[1]

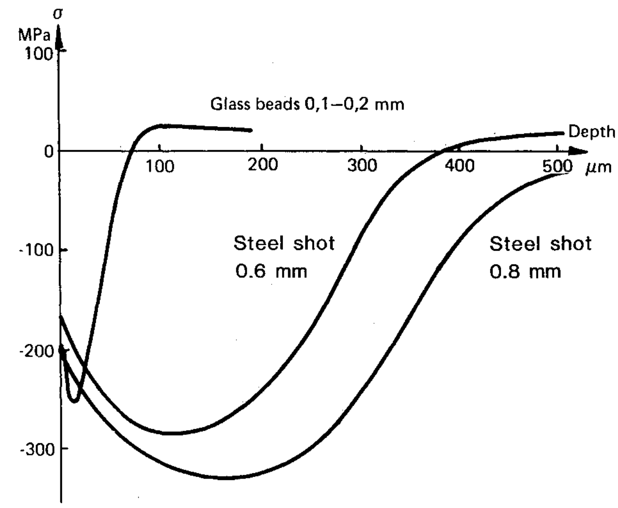

Fig. 2 Residual stress distributions achieved by peening with steel shot or glass beads.

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 fatigue behavior of the part.

The basic characteristic of the residual stress distribution of a semifinished 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 material cooled first, tensile stresses in the material cooled last). After 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. 3), the die forging with its draft angles has a much more rounded shape than the part to be machined from it. This means that, in some areas, inner corners of the final contour 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.

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. 4), which had been machined from a die forging. Figure 5 shows the pattern of tangential residual stresses found: tensile stresses close to the flanges, compressive stresses in the center 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.

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 mechanical stress relief methods applied between solution treatment and aging. 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 in this case is stretching. It is accomplished by the wedging action of the die against the draft angles of flanges and stiffeners (Fig. 6). Design elements of this kind are essential for an efficient stress relief treatment, together with the difference in the lateral dimensions between the die and workpiece, normally brought about by the difference in thermal contraction from the forging temperature between the steel die and the aluminum workpiece.

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. For this investigation, a fuselage frame forging, weighing 27 kg, with flanges and stiffeners on both sides was chosen (Fig. 7). Four forgings of each kind were made in aluminum alloy AA7010, with and without cold compression. At five locations (Fig. 8), the residual stress variation with depth below the surface was measured, using the following method: 1) surface stress measurement; 2) milling a narrow slot in the direction of the measured stress; 3) chemical removal of the surface layer cold worked by milling; 4) stress measurement in the bottom of the slot; and 5) 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 that will be removed during the machining operation.

Two examples of the measured stress distributions will be given. Figure 9 shows the variation in residual stress (in the tangential direction) to a depth of 31 mm below the surface at location 5 in the outer flange. The magnitude of residual stresses, either compressive or tensile, has been greatly reduced by the cold-compression treatment.

Figure 10 shows transverse stresses in a web section (location 2). Surprisingly, in this case, the magnitude of the residual stresses is *greater* in the cold-compressed forgings than in those that 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 noncompressed forgings, but less so in the other case or even increasing in magnitude.

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. 11). In each direction, the web material is efficiently stretched by the tool acting on the respective part of the frame, at a 90 deg angle to this

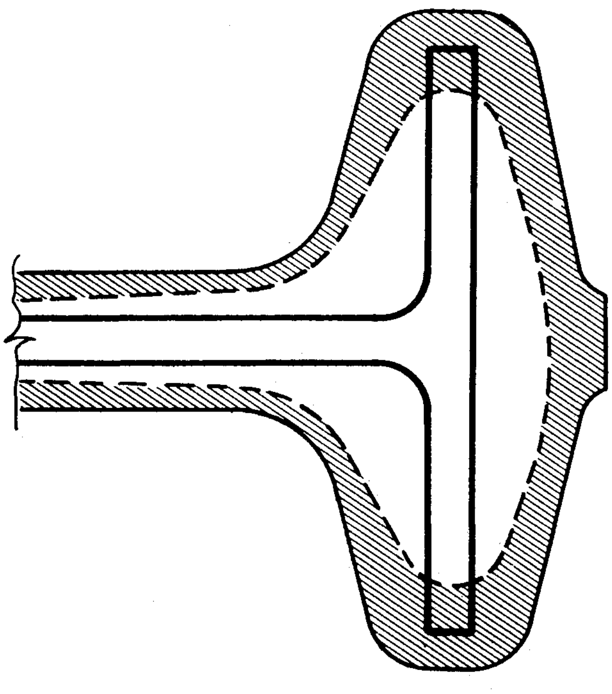

Fig. 3 Cross section of a die forging. The contours of the machined part are shown, as well as the assumed boundary between compressive and tensile residual stresses before milling.

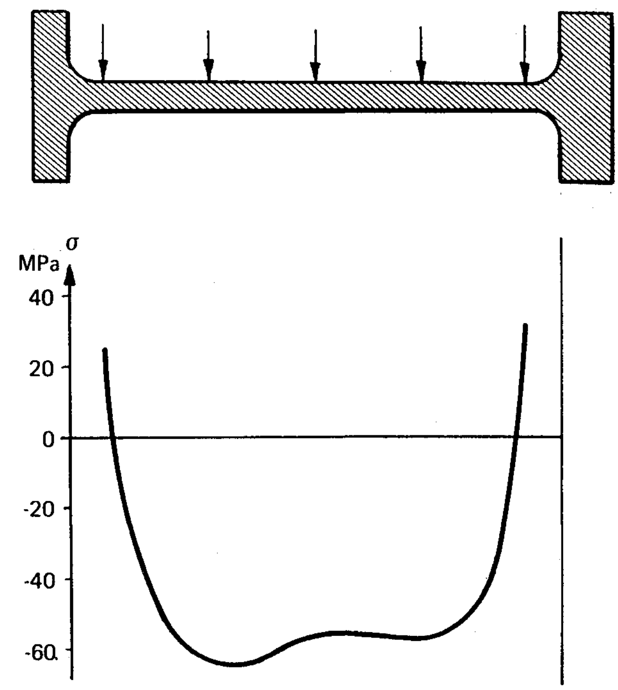

Fig. 5 Tangential residual stresses measured on wing attachment frame part.

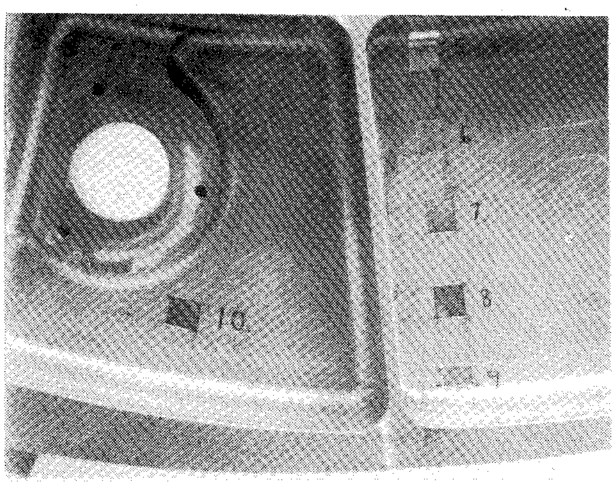

Fig. 4 Detail of wing attachment frame (locations of residual stress measurement are indicated).

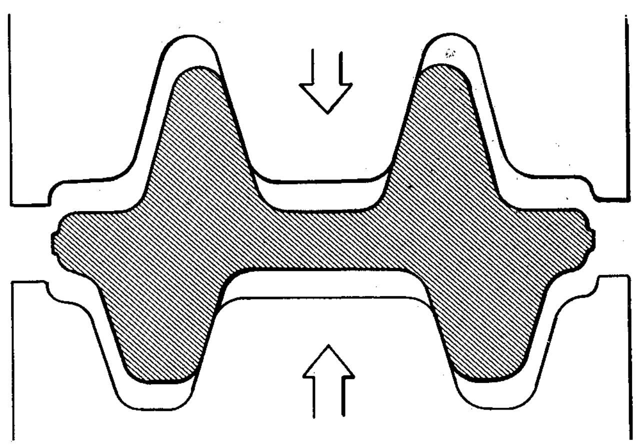

Fig. 6 Cross section of a forging being cold compressed in the forging tool.

direction (elements 2–6). The parallel frame parts (elements 1 and 7), however, are affected only via shear forces near the corners and are left virtually unstrained. 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 result 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 of sides 1 and 2, then finish milling of sides 1 and 2. After each step, the geometrical position of a large number of points on the surface of the forging 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.

Figure 12 shows graphically the displacement (normal to the plane of the forging) 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-relief operation has dramatically reduced the tendency of the forging to move perpendicular to its plane.

As for distortion in the plane of the article, the effect is noticeable but much smaller. The distortion behavior confirms the overall picture obtained from the residual stress measurement: the major effect of the stress-relief operation is a reduction of the through-thickness stress gradients.

Load-Induced Residual Stresses

Load-induced residual stresses form another group of related problems. They can be found in metallic material parts

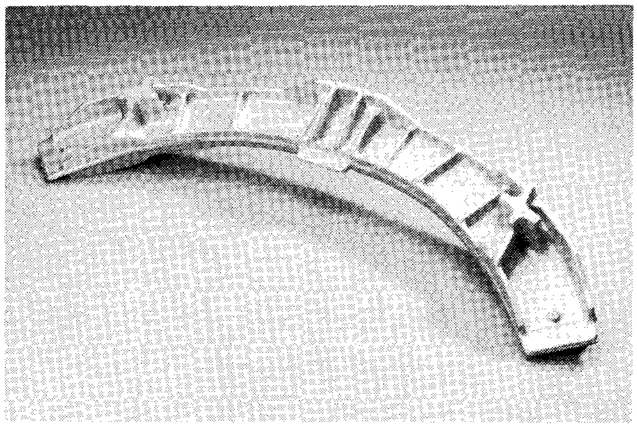

Fig. 7 Fuselage frame forging.

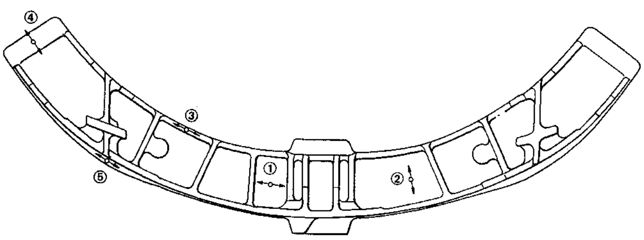

Fig. 8 Fuselage frame forging (locations of residual stress measurement are indicated).

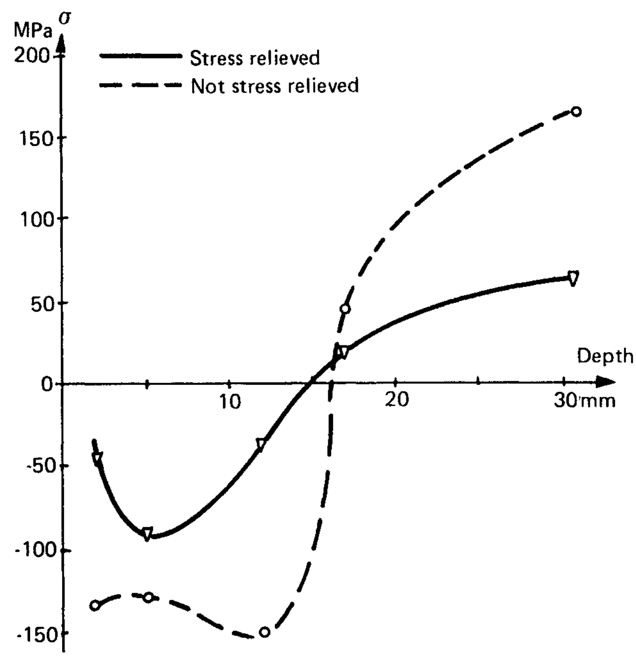

Fig. 9 Residual stress distributions in outer flange (location 5).

with noninterference-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; the effect will be especially severe if these high compressive loads are repeated a

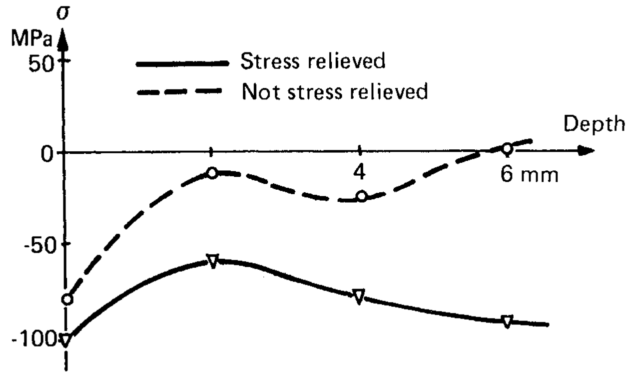

Fig. 10 Residual stress distributions in web section (location 2).

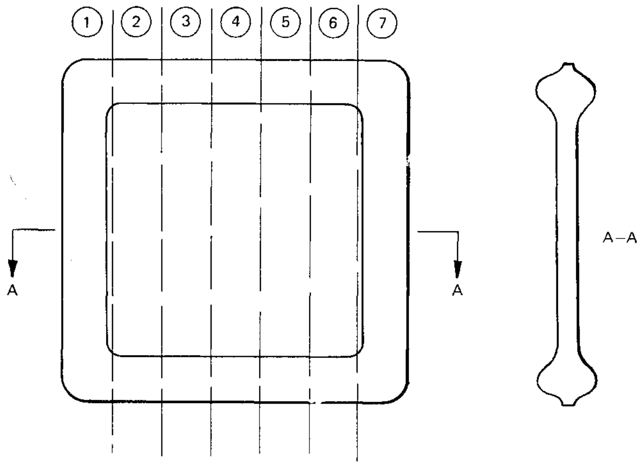

Fig. 11 Hypothetical "spar element."

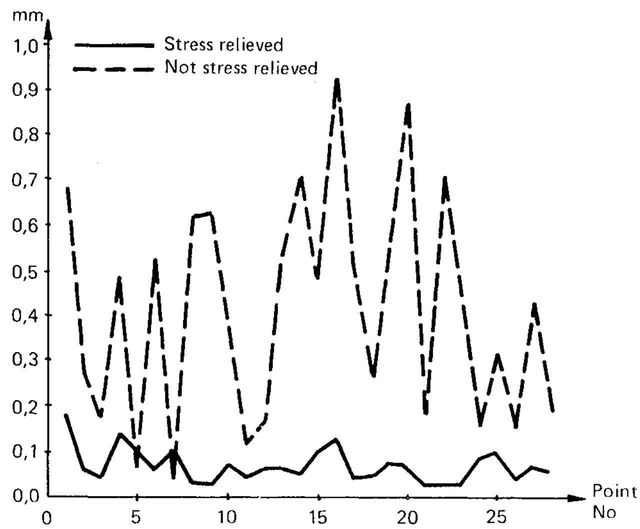

Fig. 12 Displacement of measurement points normal to the plane of the forging between two rough milling operations.

number of times during the service or test period.

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

The upper part of the main wing spar (Fig. 13) was extensively loaded in compression. The flanges had loose-

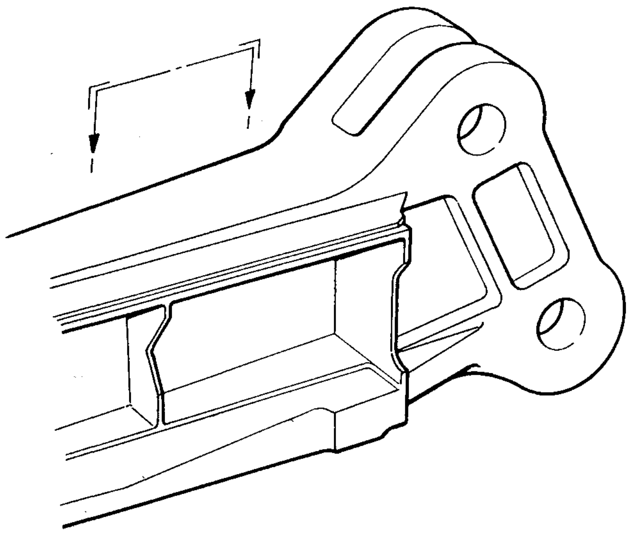

Fig. 13 Test areas of wing spar.

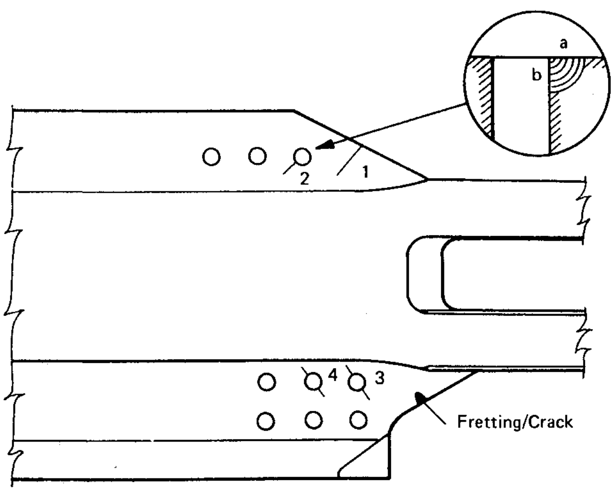

Fig. 14 Cracks in the upper compression part of the wing spar.

fitting bolt holes for joining the upper wing panels (Fig. 14). The area is located just outside the forked lug joint (view I-I in Fig. 13).

The spar was made of a die forging in the aluminum alloy AA7009 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. 15. S_{GL} denotes the nominal limit load stress.

The edge-type crack denoted 1 in the upper forward flange in Fig. 14 and the fretting fatigue crack in the rear flange were found only in the left wing spar. Corner cracks at bolt holes denoted 2–4 in Fig. 14, 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 4 of the left spar after 2800 h test simulated service time ($a \times b \approx 2 \times 2$ mm). After 5600 h, NDE inspectors found cracks at holes 2 and 3 of the left spar and the first crack of the right spar at hole 4. After 9100 h, the right spar also had cracks at holes 2 and 3. The corner cracks propagated slowly and the first fixes were introduced at 13,000 and 14,000 h, when the required factored

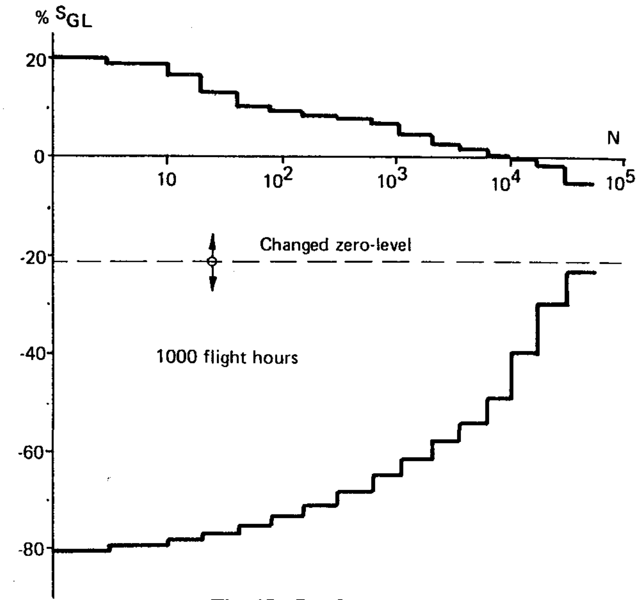

Fig. 15 Load spectrum.

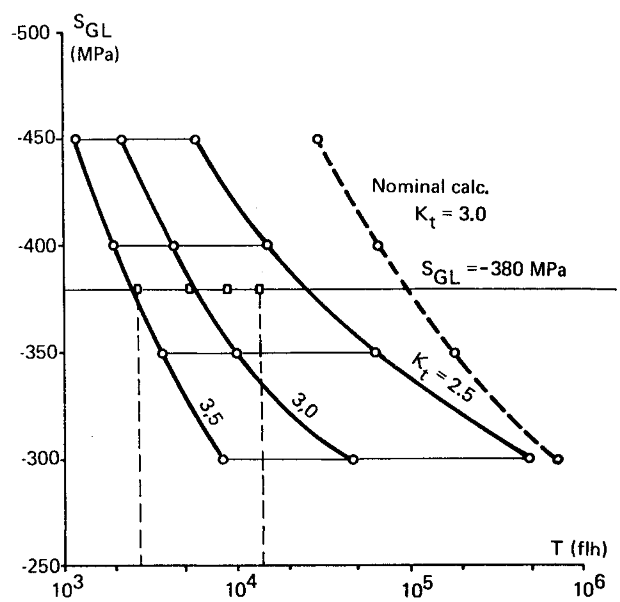

Fig. 16 Results of a cumulative damage calculation.

service time had been exceeded with good margins. The test was continued to 16,800 h, the last 2800 h at a 15% increased load level.

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 the determination of residual stresses emanating from cyclic loading.[2,3] Neuber-rule theories as well as more general methods have been studied.

Consideration of residual stresses was introduced in the Saab computer program for cumulative fatigue damage calculation, which is a program of the relative Miner type. A set of governing short peak load sequences controls the residual stresses and thus the fatigue life calculation. With regard to the case of the Viggen wing spars, the 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: 1) to represent lower quartile data, and 2) to compensate 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 be 2.5, 3.0, and 3.5 in the calculation. The value 3.0 was seen 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. 16. S_{GL} was approximately—380 MPa in the full-scale test. This stress level and the interesting times 2800, 5600 h, etc., are indicated in Fig. 16.

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 a 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.

From this, the conclusion is drawn that high spectrum loads in compression can deteriorate the fatigue strength in notched areas by creating residual tensile stresses that move the zero level of the spectrum to a far more critical position. (See Fig. 15.) A consequence of this is that noninterference-fit bolt holes should be avoided in fatigue-critical areas with high compression loads.

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 1) deep-acting, locally confined: hole expansion (e.g., sleeve cold working or "SCW"); 2) affecting a shallow surface layer, often covering the greater part of the article's surface: shot peening, glass bead peening, grit blasting, surface rolling; and 3) 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. 17). In contrast, the tangential compressive stresses emanating from roller burnishing are typically confined to a 1 mm thick zone (Fig. 18). Next to the edge of the hole, the residual stress is zero.

The deep zone of compressive stress around an expanded hole can have a substantial influence upon the design life of the part, not a priori because it will impede the propagation of a fatigue crack 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 propagation phases of a fatigue crack normally extend over the major part of the total fatigue life, although these phases are geometrically the 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 biaxial.[4]

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

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 aluminum 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.[5] 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.

Figure 19 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.

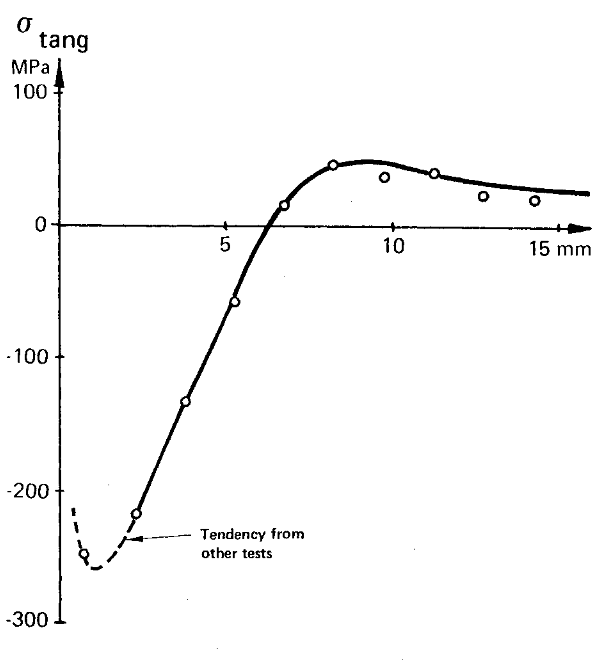

Fig. 17 Tangential residual stresses in the vicinity of an expanded hole.

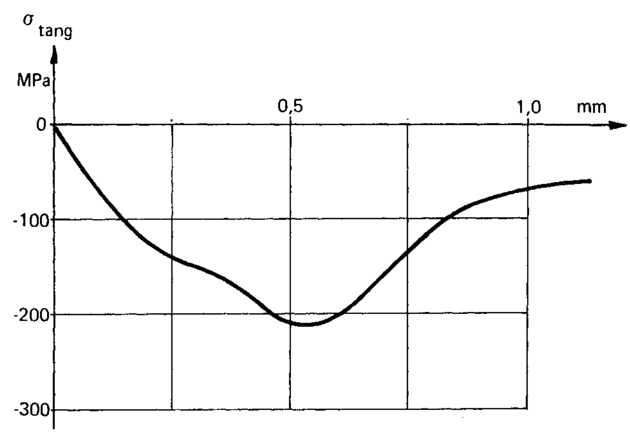

Fig. 18 Tangential residual stresses achieved by roller burnishing of a ϕ32 mm hole.

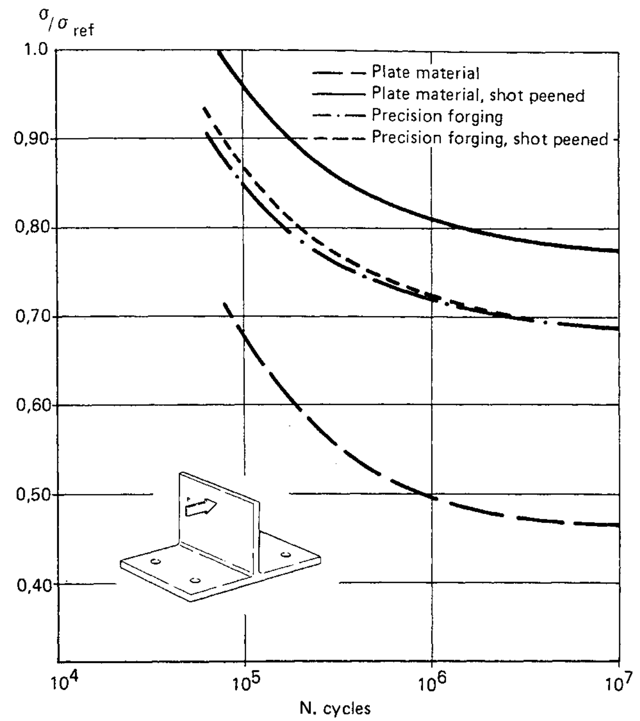

Fig. 19 ***S-N*** **diagram showing results of fatigue testing T-shaped specimens made of precision forgings and plate, respectively.**

In the precision forgings, the flow lines follow the contours of the specimen exactly. The other 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. 19 that the fatigue strength of the plate specimens was sharply reduced due to the unfavorable 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 behavior of the precision forgings. Shot peening of the critical zone could not increase the fatigue strength of the precision forgings (Fig. 19), but it had a considerable effect on the plate specimens.

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

Other cases where shot peening has proved 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 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 such as corrosion pits, tool marks, or imperfect fillet radius transitions.

Conclusions

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

A refined stress-relief 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 fatigue properties of the part 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.

Acknowledgments

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