PROCESS INTERACTIONS AND FATIGUE LIFE

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Abstract

Within the field of fatigue and damage tolerance this paper intends to build upon the current knowledge of geometric feature interactions and their effects upon fatigue life by introducing the notion of process interaction. Testing has been carried out to validate the theory that common finishing processes, such as shot peening and cold expansion, yield similar stress effects to those exhibited by the interactions of features.

1 INTRODUCTION

Since the Comet disasters [i], of the 1950's, fatigue has been a critical consideration within the aerospace industry in general but structural design in particular. There are various different methods of calculating the fatigue lives of components that have been devised. However, perhaps the most commonly used methods involve the use of stress concentration (K_t) factors derived from the geometric features contained within the design of the components. This derivation becomes a difficult proposition with the design of more geometrically complex components driven by the continuing need for considerations of the mass of components, not only for increased efficiency and range of aircraft but also, increasingly, their environmental impact. In an effort to reduce component mass features such as holes become more numerous, hence they are closer together and are more likely to have interacting stress fields. This causes problems in stress calculations as more complex geometries require more detailed simulation to accurately predict the stress effects of the multiple features.

There are many features that are required in any structure, but perhaps the most common are fastener holes, either individually, in rows or more complex arrangements as well as the combination of threaded, countersunk / counter-bored or straight holes. Methods have been developed to calculate the stress effects of these 'interacting' geometric features; however these simple features are not the only stress altering components in a structure.

An example of the interaction of stress raising features and their complex nature can be demonstrated by comparing the change in K_t when two plain holes move closer together with two countersunk holes. In the case of the plain holes the stress concentration is reduced while the countersunk holes exhibit an increase in the localised stress. Other commonly required geometric features include notches, lugs and shaft based features such as keyways.

Data on stress concentrations for individual and simple interacting features can be found in literature such as Petersons [ii], Pilkey [iii] and Roark [iv]. SCONES (Stress CONcentration Expert System), a software package developed in collaboration between BAE SYSTEMS and the University of Hull, encompasses a comprehensive quantity of data for stress concentrations on various plain and interacting features [v, vi & vii].

There are a number of commonly used processes within the aerospace industry to help deal with the problems of stress concentrations, feature interactions and environmental issues. These processes (including shot-peening, cold-expansion and anodising) have been introduced into the aerospace industry to improve properties such as wear and corrosion resistance as well as fatigue life. Some of these applied processes, such as anodising, are generally understood to be detrimental in their effects on the fatigue life of a component, whilst some such as the cold working methods are known to yield benefits in relation to the fatigue life.

However, not all aerospace manufacturers utilise all these methods for the same purpose, for instance some use shot peening for its benefit to the fatigue life of the component whilst some use it purely for peen forming (shaping or correcting the shape of components post manufacturing). When not used for its' benefit in terms of fatigue life the benefits of shot peening are not included in any fatigue calculations. However, the repeatability and, perhaps more importantly, capability of processes such as shot-peening should be considered when talking into account their benefit to the fatigue life of a component as an incorrectly applied process may not yield the life benefits assumed. Thus the presence of some of these beneficial processes is ignored in any fatigue calculations, due to the inherent uncertainty regarding their outcome, where-as detrimental process are always included. This is a safety conscious method of working, however when multiple beneficial processes overlap (process interaction) there is, potentially, the argument that some sort of life benefit can be included in any fatigue life calculations. For instance some beneficial processes such as neat/interference fit fasteners are presently included in fatigue life calculations [viii].

Consequently there must be other considerations when calculating the stress on any component. That is: what effect do any of the processes carried out on the part contribute to the overall fatigue life?

Understanding of these processes has, individually, improved over the past 50 years such that their effects upon the phenomenon known as fatigue are now better understood.

The present challenge is to understand the combination of these processes and their combined effects upon the fatigue life of the components. The paper investigates the notion of process interaction and covers fatigue tests carried out on two beneficial processes in combination, namely shot-peening and cold-expansion and assess the effects. Also issues associated with a number of other commonly used processes will be discussed.

The main aim of the research is to produce data that can be integrated into the SCONES software such that both stress concentrations due to features and process can be predicted.

2 Stress Concentrators

2.1 Geometric Stress Concentrations

Stress concentrations (K_t), regions of increased stress around a geometrical feature such as a hole or notch, have been known about for some time and investigated thoroughly over the years [ii]. Although it wasn't until relatively recently that the combination of closely related geometrical features was investigated, these combinations being known as feature interactions.

The phenomenon of feature interaction has caused engineers many headaches, as different features in combination yield different stress concentration effects, sometimes increasing stresses such that the maximum localised stress is underestimated by the engineer. Whilst conversely some instances yield lower maximum stresses and give the engineer the opportunity for more optimised design. With interacting countersunk holes increasing the effective stress concentration and two simple holes reducing the stress concentration.

Various different methods have been used through the years to calculate the overall K_t of interacting features including:

$$K_t = K_{t1}\sqrt{K_{t2}} \quad \text{[ix]} \qquad (1)$$

and,

$$K_t = K_{t1} \cdot K_{t2} \quad \text{[x]} \qquad (2)$$

Where: K_t is the overall stress concentration
K_{t1} is the maximum K_t of the 2 features
K_{t2} is the minimum K_t of the 2 features

However until the widespread use of finite element analysis techniques only few methods, including photo elastic methods, gave relatively fast, easily understood graphical representations of the stresses in a given geometry.

2.2 Fatigue Life Calculation

Fatigue life calculation is an integral part of the design process and should be carried out in tandem with any component development. This is to ensure that the part is neither over-designed nor unsuitable for the loading conditions applied during usage.

There are various methods applied to the calculation of fatigue lives but one of the most common has become the use of K_t. Within the aerospace fraternity the use of Strain Life Factors has become more common. This technique has a misleading name as it uses the principle that all the fatigue occurs elastically and not plastically as inferred by the name. Stress concentrations, due to holes, notches, keyways and threads are utilised along with the component geometry to identify an overall fatigue life.

The method also takes into account some manufacturing processes such as surface protection (anodising and chrome plating) while fatigue life improvement processes such as shot peening and cold expansion are generally ignored. However, these processes are considered on an individual basis and their effects applied by the use of an effective K_t. An effective K_t being the equivalent stress concentration of a geometric feature, of equal value, applied to the whole surface of the component as opposed to stress concentrations which only apply locally around a feature.

2.3 Process Considerations

Finishing processes are relatively common within the aerospace industry for a number of reasons. For example processes are applied to improve the corrosion and wear resistance while other processes are utilised to improve fatigue life.

Shot-peening is an ancient technology for improving the material properties of a component [xi]. Recently it has been introduced as a means of improving the fatigue properties of components by introducing compressive residual stresses into the surface of the component inhibiting crack initiation and propagation. The compressive stresses are introduced by the firing of some media (usually some spheroidal metal or glass) into the surface of the component, this causes the surface of the material to plastically deform and create the dimple effect, with the deformation setting up the residual stress under the surface [xii]. Figure 1, below, shows a typical stress distribution due to shot peening.

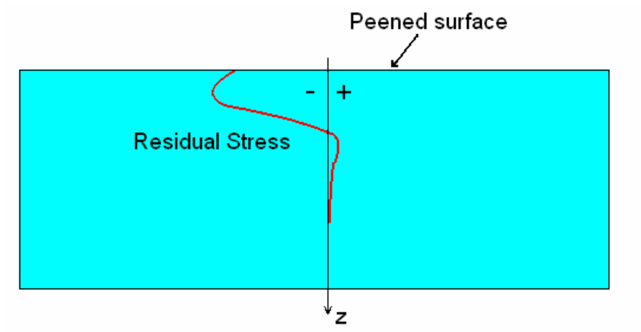

Figure 1, Showing the compressive stress layer beneath the surface of the material

Shot peening is used for various reasons, sometimes peen forming to achieve the required component shape and sometimes to improve wear and fatigue resistance (thus it is a beneficial process).

The cold-expansion of fastener holes has been recently introduced with the most popular technique emanating from a collaboration between Fatigue Technologies Inc (FTI) and Boeing [xiii]. Their method involves drawing an oversized mandrel through a sleeved hole to expand it to the required diameter such that compressive residual stresses are introduced into the surrounding material. See Figure 2, below.

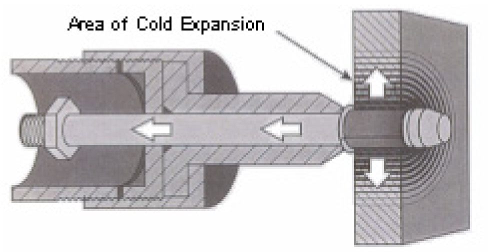

Figure 2, Showing the area of cold-expansion due to the FTI technique. (**Taken from FTI Split Sleeve Expansion leaflet**) [xiii]

Like shot-peening the compressive residual stresses inhibit crack initiation and growth. Cold expansion of fastener holes is a common process that improves the fatigue life, with many variations including the use of interference-fit fasteners and the split sleeve/mandrel method of hole expansion.

Anodising is a commonly applied corrosion protection for aluminium alloys used in industry. It is an electrolytic process which causes an increase in the thickness of the naturally occurring aluminium oxide layer. The anodic layer created by the process is known to have inherent cracks and pores running through it, thus there are many sites for crack initiation under cyclic loading. The pores are due to the growth of the layer, however cracks are due to residual stresses set up within the layer [xiv & xv]. The combination of the pores and surface cracks in the oxide layer are generally thought to reduce the fatigue life of a component, although there is some contradictory data available.

High speed machining is a common process within the aerospace industry as the requirement for highly efficient and fast production increases [xvi]; others have undertaken research into the effects of cutting forces, power and surface finish [xvi], however information is sparse as to the resulting levels of residual stresses incurred during the process. Thus, at this stage, it is undecided whether high speed machining can be classified as a beneficial or detrimental in terms of fatigue life.

All the above methods introduce various levels of residual stress into the component, with the individual processes being relatively well understood. However combinations of processes are not, generally, dealt with and as such require serious consideration during fatigue calculations when one or more finishing processes are used.

Thus the notion of Process Interaction is introduced, being similar to the notion of feature interaction in that the stress fields from several common finishing processes can overlap and cause previously unexpected localised stress levels in the component.

3 Testing

3.1 Methodology

Tensile fatigue tests have been carried out on simple dog-bone shaped samples of a 7xxx series Aluminium Alloy.

Samples were either plain drilled (5mm), drilled and the hole cold-expanded (drilled 4.8mm and expanded to 5mm) or drilled, cold expanded and the gauge area shot peened (three levels of shot peening were utilised 50 100 & 200% coverage) on one side. The cold-expansion used was the FTI methodology, described more extensively on their website [xiii]. The shot-peening was carried out to the generally adopted BAE Systems specification in collaboration with the Metal Improvement Company, this combines a multi-pass method involving both glass and steel shot.

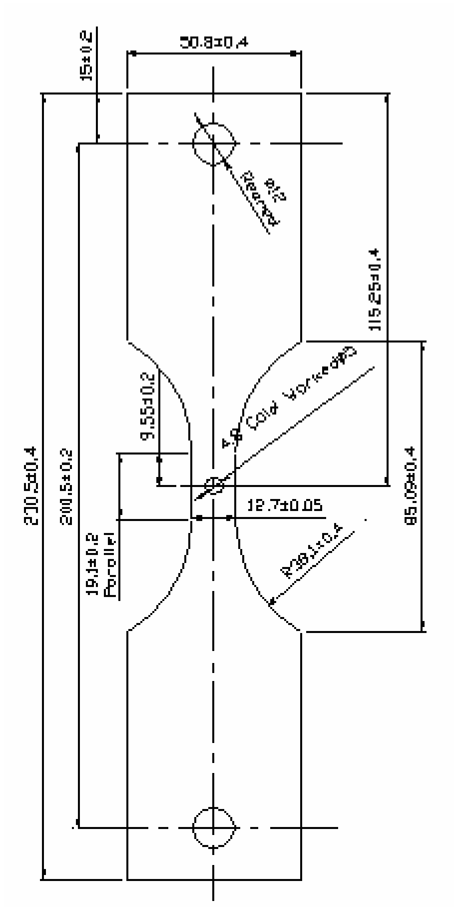

Figure 3, Diagram showing the fatigue samples

3.2 Analysis

The samples were tested to failure using a fully reversed loading spectrum and the cycles to failure measured. To aid in the analysis of the benefit of the fatigue life enhancing processes the number of cycles to crack initiation was estimated using a semi-quantitative technique. This enables analysis of the effect of the process due to the compressive residual stress and its effect on crack propagation.

The number of load cycles post crack initiation was determined by the estimation of the number of striations on the fracture surface using a modified semi-quantitative version of a technique described in "*An Atlas of Metal Fatigue*" [xvii]. The original method requiring the counting of all striations across the fracture surface, however without automated counting methods this was impractical in this instance.

The modified method involved using a Scanning Electron Microscope (SEM) to measure the distance for a series of 10 consecutive striations. This was carried out at a series of distances measured from the point of crack initiation through to the fast fracture region.

Figure 4 shows an example of the type of data recorded from one samples fracture surface. At each increment away from crack initiation a series of measurements were taken and averaged to reduce the chance of erroneous sets of results. With these results the number of striations per millimetre could be determined and given the length of the fracture surface the number of striations or loading cycles post crack initiation could be estimated.

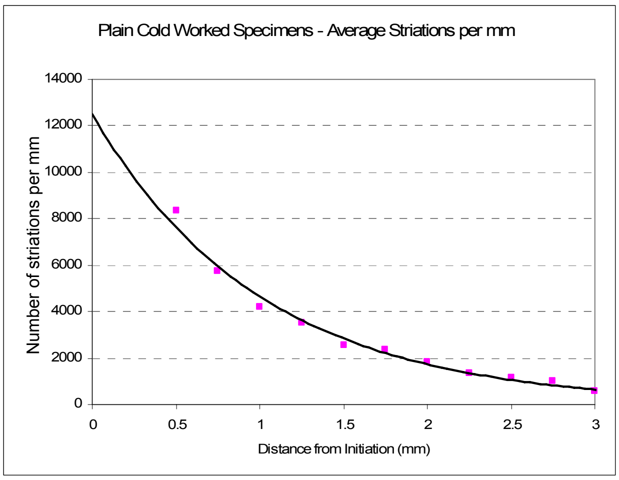

Figure 4, Showing the striations per mm for a plain drilled cold worked hole

The modified technique yielded results consistent with those described in the original technique [xvii] but enabled much faster analysis.

4 Results

The chart below, Figure 5, shows the average life to failure for the samples when tested.

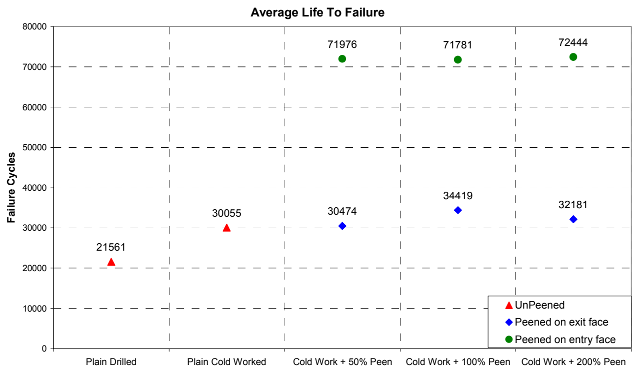

Figure 5, Average life to failure of the samples

It can be seen in Figure 5 that there are differences in the fatigue life of the samples with cold working yielding almost 40% life improvement over plain drilled holes. It can also be seen that shot peening the exit face of the samples yielded no discernable life improvement over plain cold worked while shot peening the entry face yielded approximately 120% life improvement over plain cold worked and when the exit face was shot peened.

Under analysis on the SEM the untreated, plain drilled samples failed with multiple cracks initiating through the hole, Figure 6, while all the cold worked samples appeared to fail after cracks initiated at the mandrel entrance face, Figure 7 is an example of this.

It can be seen that the plain hole, Figure 6, failed due to the initiation of several intertwining cracks. These cracks appear to start on different planes within the material through the axis of the hole rather than either of the sample faces. The direction of the crack propagation can be determined due to the fan shaped marks emanating from the initiation point, this also aids in the determination of the initiation point.

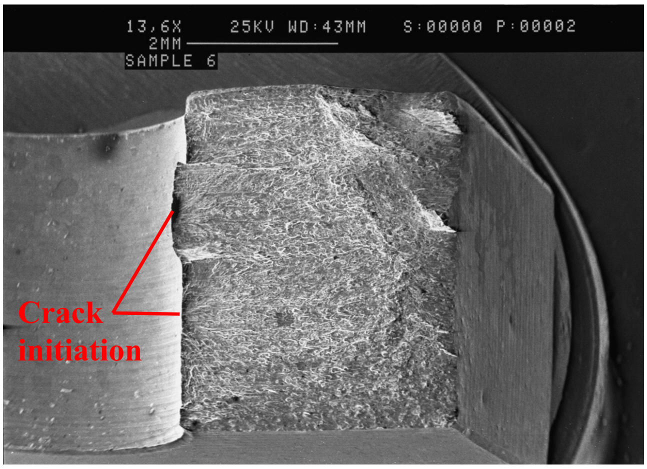

Figure 6, Multiple Crack Initiation sites on a plain drilled sample

It can be seen from the micrographs, Figure 7, that there is some plastic deformation due to the method used to draw the mandrel through the material.

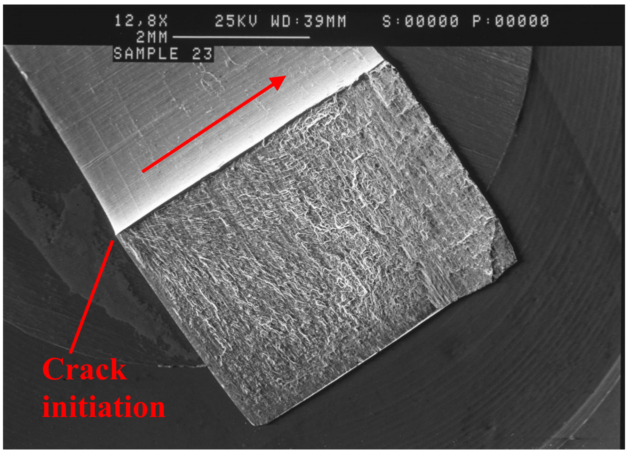

Figure 7, Crack initiation located at entry face of hole (arrow shows cold-working direction)

This deformation can be seen more clearly in Figure 8, overleaf. This gives one an impression of the forces required to create the cold expansion within the hole as well as the direction that it occurred. This is a useful diagnostic tool as it tells us at which face (entry or exit) that the crack initiated from.

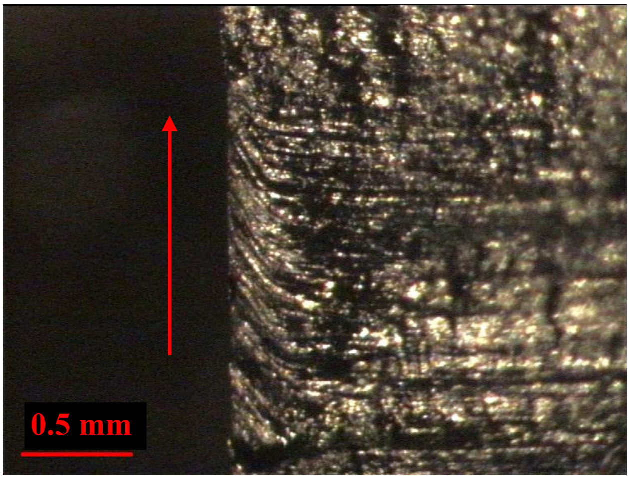

Figure 8, Plastic deformation due to the application of cold-expansion technique (arrow shows direction of flow)

5 Discussion

It can be seen from the results that the effects of both the treatments investigated improve the fatigue life of the component. However when the components were shot-peened it can be seen that there are two levels of fatigue life, this can be explained by the combination or interaction between the direction of the cold-working and the side of the component that was shot-peened.

Using optical microscopy to analyse the crack initiation sites it can be said that the tests carried out during this research agrees with previous work including [xviii & xix] which determined that the use of cold-expansion causes crack initiation to occur at the mandrel entrance face of the hole, as the residual compressive stress is greater at the exit face. Thus when the mandrel exit face is peened then there is little or no benefit to the fatigue life. However, when the mandrel entrance face is peened there is a significant life improvement. This is because the residual stresses introduced by the peening increase the propagation time of cracks. It can also be seen from the results that the level of shot-peening doesn't have much of an effect with regard to the level of fatigue life improvement. However there is evidence that the exit face peen is best carried out at 100% coverage. While there may be beneficial compressive stresses induced they may be reduced, non-existent or in some cases residual tensile stresses, present in the 'bare' patches where peening has not occurred [xx].

Anecdotally crack initiation occurs at around two thirds of the fatigue life, during these analyses it has been shown that this is more or less the case with the plain drilled samples, however the cold working led to a reduction in the quantity of life endured before any cracks initiated. However with the cold expansion the samples endured a fatigue life of around a 50% greater than the plain samples. Thus, although cracks occurred earlier in the life, the compressive residual stress in the component aids in the prevention of crack propagation helping to increase the overall life. Also it should be noted that the different orientation of the crack propagation will affect the proportion of fatigue life post crack initiation. In the case of the plain drilled samples the cracks propagate across the narrow part of the sample away from the axis of the hole. However the cold-worked samples (regardless of shot peening) have cracks initiating at the conjunction of hole and sample face meaning that the cracks can only propagate away and hence have to cover more of the material before fast fracture can occur. This may, in conjunction with the compressive residual stresses, explain how the cracks occur at an earlier stage in the overall fatigue life whilst increasing the overall lifespan of the sample.

6 Conclusions

The shot-peening of the mandrel exit face shows little or no additional benefit to the fatigue life of the component.

The shot-peening of the mandrel entrance face has significantly improved the fatigue life of the component.

The level of the shot peening has little effect on the life improvement of the component.

Finishing process combinations, such as cold-expansion and shot-peening, can be engineered such that their stress fields interact to create a significant improvement in the fatigue life of a component.

7 Future Work

Future challenges include:

The application of the residual stresses into the software package SCONES and to develop a comprehensive stress engineers toolbox.

The development of the notion of interacting processes and further investigation into different processes, including their effects on the localised and general stress fields.

8 Acknowledgments

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