EFFECT OF LARGE LOCAL PLASTIC FLOW ON THE FATIGUE LIFE OF METALLIC MATERIALS

G. S. Wang and A. F. Blom
Aeronautics Division, The Swedish Defence Research Agency, Sweden

ABSTRACT

This research shows that plastic deformation affects fatigue life through creation of a large number of micro cracks in material matrix. As a result, the crack initiation is accelerated and fatigue life is reduced. The micro cracks created by plastic deformation also reduce the scatter in fatigue life. Although there are indications that plastic deformation may affect crack growth rate, the tests showed that the crack growth rate is only marginally affected. In an engineering treatment, the effect of plastic deformation on fatigue crack growth rate may be ignored.

1 INTRODUCTION

One of the qualities of metallic materials is their capability to tolerate large plastic deformations. Fig.1 shows en example for the stress-strain relation of 2024-T3 aluminium alloy, with a failure strain of more than 18% even after the strain hardening of a full load cycle. Plastic deformation in structures has its beneficial effects. It can change the shape of local sharp notches to reduce stress concentration, induce residual stresses acting against applied load, and may strengthen the material due to strain hardening. As a result, a metallic structure may exhibit remarkable integrity even after various harmful production methods like welding, riveting, and cutting techniques. This behaviour allows high stress concentrations and residual stresses in structures due to welding, contact singularities in fasteners, sharp notches from cutting tools, and parasitic stress due to integrated part design.

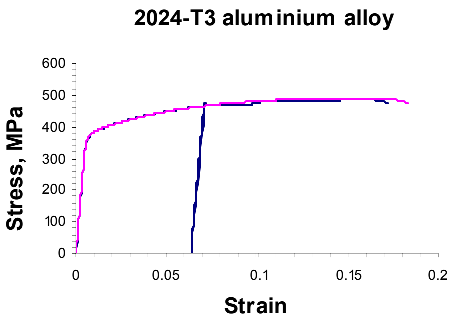

Fig.1

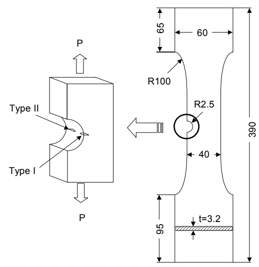

Fig.2

The trend towards an integrated fatigue analysis tends to include both stages of crack initiation and propagation, which requires profound understanding of the entire fatigue process. While some success in this new methodology has been achieved for well-controlled test condition, structural problems pose firm challenges. The integrated analysis methodology requires much higher level of understanding of basic material behaviour. Plastic flow, for example, is one of them. In addition, large plastic flow often occurs at the worst spot in a structure, at which fatigue cracks are frequently initiated, leading to catastrophic structural failure.

2 FATIGUE TEST AND RESULTS

To understand how large plastic flow may affect fatigue properties of material, a special fatigue test method is designed. A well-known aluminium alloy (2024-T3) widely used in the aeronautical industry is used for this investigation. Single notched specimens were used in the investigation, see Fig.2. The basic principle of the test set-up is to apply a substantial plastic deformation before any fatigue loading is applied. The fatigue crack initiation and propagation are then monitored using a state of the art laser speckle technique, see Fig.3. The observation is further implemented with scanning electronic microscope (SEM) fractographic inspections.

To evaluate how the plastic deformation may affect fatigue life, fatigue tests are performed at various load levels under a constant amplitude loading condition at a stress ratio of $R = 0.1$. Two groups of specimens are tested: one with original sheet, and the other with specimens having their notches cut after a static strain of 10%.

The test results are shown in Fig.4. The tests show that the overall fatigue limit is higher than that of the AGARD [i] small crack tests using the same material and similar specimens. The increased fatigue limit may be mainly due to surface condition at the notch. While AGARD specimens were carefully prepared using a chemical polish procedure to remove a layer of material at the notch to improve smoothness of the surface, and to remove residual stresses, the present specimens have the "as produced" condition of surface.

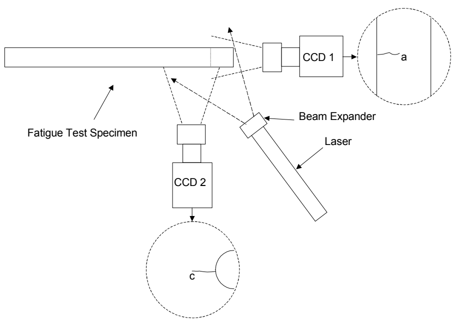

Fig.3

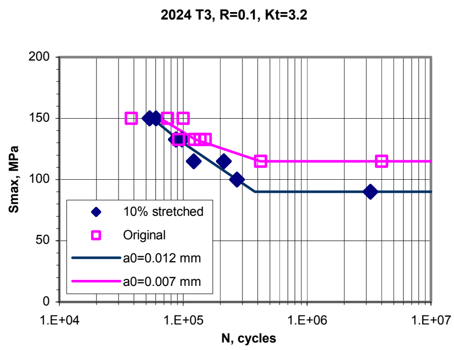

Fig.4

The fatigue limit of original sheets is so high that most of the tests are possible only after an initial local yield has occurred at the notch. The scatter in fatigue life is large even at high loads, indicating that crack growth rate, initial defects, as well as crack initiation may have large deviation. The fatigue limit seems to be located just below a stress level of 115 MPa. Consider the specimens having a stress concentration of 3.2, the local stress on the notch is near the yield stress at fatigue limit.

The pre-plastic deformation changes significantly the geometry of the specimen. At 10% strain, the length of specimen is stretched about 9.2% and the area of cross section is reduced about 8%.

The fatigue load is determined based on the new cross section to keep the stress the same. The fatigue test results of the pre-deformed specimens are shown in Fig.4 as solid symbols.

Generally, the S-N curve of the pre-deformed specimens is lower than that of the original sheets. The difference becomes larger at low stress levels. When load increases, the difference between pre-deformed specimens and original specimens is narrowed. Taking account for the plastic yield at the notch, this tendency is rather natural. At high stress levels, the gross yield at the notch becomes so large that the original sheets may have similar pre-deformation condition as the pre-deformed ones. This will narrow the difference between original and pre-deformed specimens.

While the average difference in fatigue life is slightly more than 23% at a stress of 133 MPa, with original specimens having longer fatigue lives, the original sheet has at least 3 and a half times longer fatigue life at a stress level of 115 MPa, compared to the shortest fatigue lives, see Fig.4. At the highest stress level, the difference becomes marginal with some of the fatigue data for the original specimens having even shorter fatigue lives than those of the pre-deformed specimens.

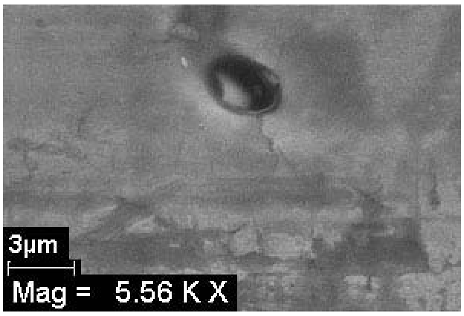

Fig.5

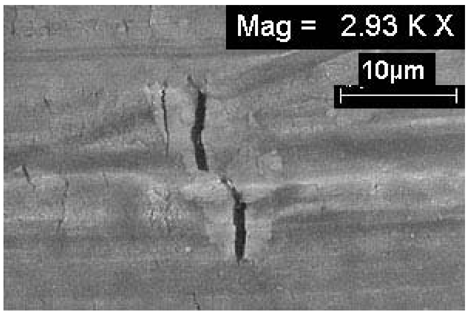

Fig.6

The effect of pre-deformation on fatigue strength depends on fatigue life requirement. For example at a target life of 10^5 cycles, there is only about 6%'s reduction in fatigue strength due to plastic deformation. At a target life of 10^6 cycles, the reduction in fatigue strength can be as large as more than 20%. This reduction in fatigue strength can result in a considerable impact on the sizing of structures when the fatigue strength is translated into the weight and the fuel consumption. This aspect should be specially addressed when spectrum loading is considered since overloads, thought they seldom occur, may create a pre-deformation condition which reduces crack initiation time.

3 DISCUSSIONS AND CONCLUSIONS

The crack initiation and propagation is monitored with either laser or white light illuminated CCD camera (see Fig.3), and the fatigue crack growth is evaluated based on image analyses. Microscopic and scanning electronic microscope inspections have been made both on the specimen surface and on the fatigue and fracture surfaces to identify fatigue crack initiation and growth mechanism for original as well as plastic deformed material.

The research shows that plastic deformation affects fatigue life through creation of a large number of micro-cracks, see Fig.6 compared to Fig.5 for original condition. As a result, the crack initiation is accelerated and fatigue life is reduced. The micro cracks created by plastic deformation also reduce the scatter in fatigue life. Although there are indications that plastic deformation may affect crack growth rate, the tests showed that the crack growth rate is only marginally affected, see

Fig.7. In an engineering treatment, the effect of plastic deformation on fatigue crack growth rate may be ignored.

The investigation indicates that different initial crack sizes may be needed in analysing the fatigue crack growth depending on gross plastic deformation, the stress level, and how many cracks may participate crack initiation process.

Furthermore, a methodology is presented to deal with local plastic flow for structural problems. The method is based on matured linear fracture mechanics solutions to deal with large plasticity problem using the concept of strip yield model and superposition methods. The analyses and experiments show that conventional fatigue analysis methodologies have serious shortcomings. However, this investigation shows that with a careful consideration and a better understanding of material fatigue behaviour, it is possible to establish an integrated analytical method to evaluate fatigue problems even if large local plastic flow may occur. The results indicate that practical solutions may be found even for a classical difficult problem when real structural applications are considered.

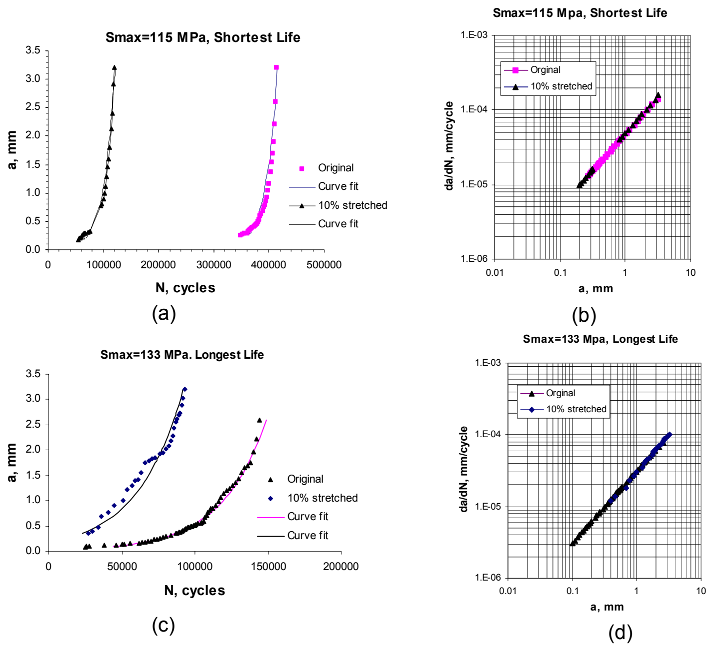

Fig.7

REFERENCE

[i] Edwards PR and Newman JC, Jr., "An AGARD supplement test programme on the behaviour of short cracks under constant amplitude and aircraft spectrum loading", AGARD-R-767, ISBN 92-835-0577-8, August 1990.