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Prediction of fatigue lives at stress raising features in a high strength steel

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The fatigue properties of the high strength stainless steel CSS42L have been evaluated under strain and stress controlled conditions. The results have been used to derive a predictive approach based on the Walker strain equation. Accurate predictions are obtained for VCN and DEN specimens although the lower stress concentration RCN specimen is shown to compare more readily with plain specimen stress controlled data. The difference in fatigue life between the notched specimens has been found to be related to the crack propagation phase where the crack grows through material which has previously been operating under reduced stress conditions.

1. Introduction

The drive for increased efficiency in the aerospace sector, based on the ACARE 2020 targets, will require contributions across the industry. Evolution of the gas turbine engine through weight reductions and increased operating temperatures will offer a significant contribution as will further developments in airframe structures and air traffic management. The increased power offered by modern gas turbine engines however, has allowed for the production of larger aircraft which offer efficiency savings through increased passenger travel, and hence a lower fuel consumption per passenger kilometre.

The increased weight of modern aircraft means that ever increasing demands are placed on materials used for load bearing parts requiring high strength, good fracture toughness and fatigue resistance, such as landing gear. The typical requirements for these components have led to the use of ultra high strength steels such as 300 M although the opportunity for weight saving has led to the employment of high strength beta titanium alloys such as Ti5-3-3 or even potentially organic matrix composites (OMCs) [1]. However, these material systems come at an increased cost, which must be offset against the improvements in density and also corrosion resistance.

The economic case for high strength stainless steels is further improved by the development of new alloys such as CSS42L, which seeks to balance strength with improved corrosion resistance. CSS42L is a case carburizable stainless steel capable of reasonable operation at temperatures over 400 °C, although this is of less importance for landing gear applications than other components where the alloy has found employment, typically cams, shafts and bolts.

Of great significance to the employment of these alloys, however, is the provision to accurately life the material under a range of loading conditions and in particular, to characterise the effects of stress raising features which may produce localised plastic deformation which can act as a source for fatigue crack initiation. Previous work [2,3] has shown that notched specimen fatigue behaviour can most accurately be predicted through use of strain control fatigue results. In principle, material at the notch root will initially be undergoing a higher stress than surrounding material and as such, will be constrained by this surrounding material which undergoes less deformation. Therefore, under these conditions the material can now be considered to be under a strain controlled rather than stress controlled type of deformation. There is however little information available detailing the degree of constraint necessary to produce these conditions, where a transition to this type of behaviour might occur and furthermore whether it is likely to be material, temperature or environment dependent.

In considering the current work it is necessary to appreciate the previous work which has been conducted in the field so that an appropriate method can be followed if necessary. Glinka [4–6] previously developed an analytical method to calculate the local strains at notches when the deformation is non-linear based on the equivalent strain energy density. The technique assumes the

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strain energy density in the plastic zone ahead of a notch can be calculated on the basis of the elastic stress–strain solution.

Duran [7] proposed a series of modifications to Glinka's method in order to calculate the inelastic stress–strain fields at notched regions as the stress state becomes biaxial or triaxial. Whereas Glinka's method was designed to estimate stress–strain values at the notch tip after yielding, and therefore low cycle fatigue (LCF) design, Duran's modified technique focuses on the stress fields at the tip of the notch for high cycle fatigue (HCF) considerations. Results showed that the technique offers much promise for monotonic loading and the potential of extending them for fatigue loading under HCF conditions.

Golos and Ellyin [8] also proposed a prediction method for fatigue initiation lives in notched components through a strain energy density approach. This technique has shown promise in predicting notched fatigue behaviour [9] over more traditional strain based methods.

In addition to the more analytical based approaches to determine local notch stresses and strains, numerical methods such as Finite Element (FE), are often employed and have found to be particularly effective in establishing the elastic–plastic stress state during cyclic loading [10,11].

With reference to the previous literature, the current work seeks to evaluate the results of three notched specimen types designed to be representative of industrial stress raising features. Based on a limited amount of fatigue data an appropriate fatigue lifing method has been proposed from which notched specimen predictions can be made. Conclusions can then be drawn regarding the influence of constraint and the most appropriate method of predicting fatigue life.

2. Experimental method

Commercially available CSS42L was obtained for the research with a chemical composition as detailed in Table 1. A heat treatment procedure was employed in which the material was heated to and maintained at 885 °C for 1 h, then gas quenched down to room temperature. After being cooled to −73 °C and held for 1 h, the material was tempered at 482 °C for 5 h. The microstructure of the material in its tempered form is displayed in Fig. 1.

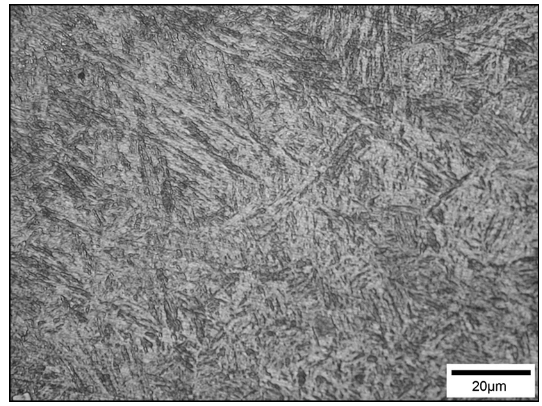

Fig. 1. Microstructure of tempered CSS42L.

A total of 25 fatigue tests were performed on a servo-hydraulic test machine, 22 under stress controlled conditions and an additional three under strain control, where an MTS 12 mm gauge length extensometer was employed to control strain. Testing was conducted at 20 °C under controlled laboratory conditions, and an R ratio of 0 was employed whether testing was conducted under stress control ($R_\sigma = 0$) or strain control ($R_\varepsilon = 0$) and a trapezoidal 1-1-1-1 waveform was applied. The same test specimen was utilised for either stress or strain controlled testing and consisted of a 6 mm diameter and 12 mm parallel length. Stress or strain was varied from test to test in order to produce a relevant low cycle fatigue curve.

Notched specimen testing was conducted on three different geometries considered to be representative of typical stress raising features in engineering components. These specimens are displayed in Fig. 2. The Round-cylindrical notch (RCN) (Fig. 2(a)) has a stress concentration factor, K_t of 1.4, the Double-edged notch (DEN) (Fig. 2(b)) a K_t of 1.78 and the V-cylindrical notch (VCN) (Fig. 2(c)) a K_t of 2.7. Each of these were determined by finite element analysis (FEA). Testing was again conducted at an R ratio of 0 and fatigue curves were generated as previously described. Each notched test piece had potential difference (PD) monitoring attached in an attempt to determine crack initiation during the test through a pulsed direct current.

3. Results

Fatigue tests produced under strain control loading allowed for the recording of stress–strain hysteresis loops, from which plots of applied stress vs. cycles could be derived, required for lifing approaches such as the Walker strain approach. An example of these hysteresis loops is shown in Fig. 3, for a peak applied strain of 1% at an R ratio of 0. Full details of the three experiments undertaken in strain control are displayed in Table 2. Based on these experiments and further load controlled fatigue tests, Fig. 4 illustrates the fatigue response of plain specimens along with that of the three notch types previously described. Strain controlled data is plotted on the y-axis as stabilised stress range, defined as the values calculated at $N_f/2$, where N_f is the strain controlled fatigue life. Load controlled fatigue data is plotted as the nominal stress against fatigue life. Data points designated with an arrow indicate a run out after 1,000,000 cycles.

Clearly evident in the data is the reduction in fatigue life brought about by the introduction of a notch to the specimen. A significant reduction in fatigue life is observed in both the RCN and DEN notch geometries with further reductions in the VCN specimen.

Fig. 5 provides further detail of these results by illustrating the potential difference across the notch roots for a selection of the tested notched specimens. Despite the relatively large distance between PD wires it is clear that a clean response is found, allowing for accurate determination of the onset of long crack growth in each case. Initially apparent is the significant difference in crack initiation between the different notch types. Consistently in the VCN specimen a detectable crack forms at approximately 54% of the total fatigue life. However, in both the RCN and DEN specimens cracks are not detected until approximately 73% and 92% respectively. Table 3 provides details about the initiation and propagation lives of specimens for which PD readings were recorded.

Table 1
Chemical composition of CSS42L.

Ni	Cr	Mn	Cu	Mo	Nb	C	Si	P	S	Co	V	W	Fe
2.02	13.89	0.18	0.07	4.77	0.02	0.14	0.14	0.008	0.002	12.38	0.62	0.04	Bal