Chapter 1

Introduction

1.1 Friction-Stir Welding (FSW)

FSW is a solid-state joining process (the metal is not melted) that uses a third body tool to join two surfaces. Heat is generated between the tool and material which leads to a very soft region near the FSW tool. FSW then mechanically intermixes the two pieces of metal at the place of the joint with pressure.

1.2 Advantages of Friction Stir Welding

The solid-state nature of FSW leads to several advantages over fusion welding methods as problems associated with cooling from the liquid phase are avoided. Issues such as porosity, solute redistribution, solidification cracking and liquation cracking do not arise during FSW. In general, FSW has been found to produce a low concentration of defects and is very tolerant of variations in parameters and materials.

1.3 Finite Element Method (FEM)

In mathematics, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses variation methods (the calculus of variations) to minimise an error function and produce a stable solution. Analogous to the idea that connecting many tiny straight lines can approximate a larger circle, FEM encompasses all the methods for connecting many simple element equations over many small sub domains, named finite elements, to approximate a more complex equation over a larger.

1.4 About AA 7075-T6

The T6 temper AA 7075 has an ultimate tensile strength of 74,000–78,000 psi (510–572 MPa) and yield strength of at least 63,000–69,000 psi (434–503 MPa). It has a failure elongation of 5–11%, The T6 temper is usually achieved by homogenizing the cast 7075 at 450 C for several hours, and then aging at 120 C for 24 hours. This yields the peak strength for the 7075 alloy. The strength is derived mainly from finely dispersed eta and eta' precipitates both within grains and along grain boundaries.

1.5 Fatigue Crack Growth

Cracks compromise the integrity of engineering materials and structures. Under applied stress, a crack exceeding a critical size will suddenly advance, breaking the cracked member into two or more pieces. This failure mode is called fracture. Even sub-critical cracks may propagate to a critical size if crack growth occurs during cyclic (or fatigue) loading. Crack growth resulting from cyclic loading is called fatigue crack growth (FCG). Because all engineering materials contain microstructural defects that may produce fatigue cracks, a damage tolerant design philosophy was developed to prevent fatigue failure in crack sensitive structures. Damage tolerant design acknowledges the presence of cracks in engineering materials, and is used when cracks are expected. Both sudden fracture, and fracture after FCG, must be considered as failure modes. Because initial critical defects are rare in well-designed engineering structures [17], FCG is of primary concern here. The stress intensity factor, K, was initially used to quantify crack-tip damage for fracture scenarios. Fracture was shown to occur when the crack-tip stress intensity factor reached a critical value, K_c, independent of crack size or net applied stress [33]. This observation led to the concept of crack similitude, *i.e.* cracks of different length will fracture at the same K_c. Fracture mechanics analysis, and crack similitudes were modified for fatigue cracks [60]. Fatigue crack growth rates (increment of crack growth per load cycle, da/dN) were related to ΔK, the cyclic range of crack-tip stress intensity, for constant amplitude loading and a schematic of typical constant amplitude load cycles is shown in Fig. 1.1, where the stress intensity factor, K, is plotted as a function of time. As indicated by the solid curve, the stress intensity factor oscillates between minimum and maximum values, K_{min} and K_{max}, respectively. Arrows indicate change in K with increasing time. ΔK is shown schematically on the right side of the figure, and is defined as (K_{max} - K_{min}). Another useful parameter to describe constant amplitude loading is the load ratio, R, defined in the Fig.1.1 as the ratio of K_{min}, and K_{max} (i.e., $R = K_{min} / K_{max}$). Paris implemented that similitude exists for fatigue cracks subject to the same ΔK. In other words, fatigue cracks of different length but subject to the same ΔK will grow at the same FCG rate, da/dN. Therefore, FCG data obtained from laboratory specimens (of convenient size) can be used to predict the FCG response for any crack configuration.

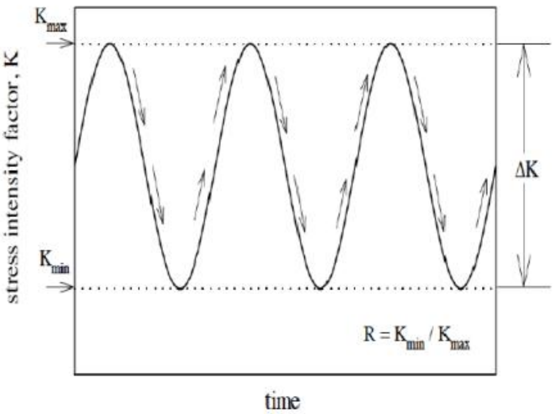

Fig. 1.1 Schematic of Constant Amplitude Load Cycles, Where the Crack-Tip Stress Intensity Factor, K, is plotted against Time.[37]

1.6 Fatigue Crack Growth Behaviour of Engineering Metals

A schematic of typical (constant R) FCG behaviour for engineering metals is shown in Fig. 1.2, where the logarithm of FCG rate, log (da/dN), is plotted against log

(ΔK). FCG behaviour, indicated by the solid curve, is divided into three distinct regions by vertical dotted lines in the Fig.1.2. At intermediate values of ΔK, (typically between 5, and 20 MPa $m^{1/2}$ for aluminum alloys at R = 0) the FCG curve is nearly linear on log-log plots. This region, called the Paris regime, is labeled in Fig. 1.2. Taking advantage of this linear relation, Paris presented an equation relating FCG rates (da/dN) to ΔK using two empirical material parameters (C and m) as shown in equation 1.1 [4]. The slope of the FCG curve in the Paris regime, m, is shown on the figure and ranges from 2 to 4 for most engineering metals. As ΔK increases beyond the Paris regime, unstable crack growth occurs. This region is shown to the right of the Paris regime in Fig. 1.2. Here, the FCG curve becomes steep (i.e. da/dN increases rapidly with increasing ΔK) as K_{max} approaches the fracture toughness, K_c, or large scale yielding occurs.

$$da/dN = C(\Delta K)^m \qquad \text{.........................(1.1)}$$

As ΔK decreases into the threshold region, the FCG curve becomes steep as da/dN rapidly decreases with ΔK reduction. Presumably, a threshold ΔK is reached, ΔK_{th}, below which no detectable FCG occurs. Threshold FCG is of practical interest for two reasons.

First, the concept of FCG threshold is useful from a design stand point. For applications where initial cracks or defects are unavoidable, FCG (ultimately leading to failure) can be avoided if $\Delta K < \Delta K_{th}$. Second, under constant cyclic loads a (naturally forming) fatigue crack grows faster as crack length increases, so the majority of fatigue life is spent propagating a small crack under threshold conditions. Paris and unstable FCG behaviour are typically limited to a small portion of the total fatigue life.

1.7 Damage Tolerant Design

Damage tolerant design was developed to prevent structural failure of components where fatigue cracking is likely. Fatigue life is calculated using service conditions, known FCG behavior, and crack sizes found by careful inspection procedures. If no crack is found, the most damaging flaw or crack that cannot be reliably detected is assumed to exist.

This conservative design philosophy has been successfully used when FCG and fracture limits the service life of a structure. Using damage tolerant analysis, failure can be prevented by two means:

1. Limiting service life to the cycles required for the longest crack to propagate failure
2. Ensuring that, the most damaging (longest) crack will not propagate, i.e. $\Delta K < \Delta K_{th}$

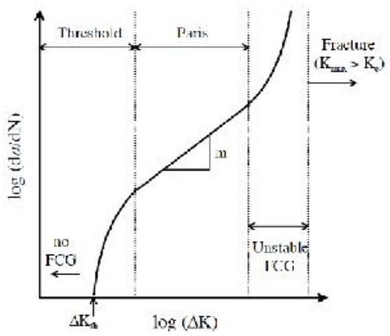

Fig.1.2 Schematic of Typical FCG Data, Plotted As Log (Da/Dn) Vs. Log (ΔK).
The FCG Behaviour is divided into three regions
(Threshold, Paris, and Unstable FCG Regions) [37]

The latter option is most attractive when designing for long fatigue lives, and is the subject of this discussion. In these cases, ΔK_{th} and K_c are used as design parameters for FCG and fracture, respectively. An idealised schematic of ΔK versus K_{max} is shown in Fig. 1.3. Values corresponding to ΔK_{th} and K_c are labeled in the figure. If K_{max} exceeds K_c, fracture will occur as indicated on the right side of Fig. 1.3.

At $\Delta K > \Delta K_{th}$, FCG will occur (likely leading to fracture) as shown at the top of the Fig. 1.3. A safe region exists where, $\Delta K < \Delta K_{th}$, and $K_{max} < K_c$, indicated by the shaded region at the bottom of Fig. 1.3. Existing cracks are considered favorable if the crack-tip stress state lies within these safe bounds.

Damage tolerant design has been used to decrease structural weight without sacrificing safety. The most common way to reduce ΔK (below ΔK_{th}) in an engineering component is to decrease stress levels. Because stress reduction is normally accomplished by increasing the load bearing area, increased weight results as an undesirable by-product. Weight increases are especially troublesome for aircraft and spacecraft applications where lightweight, durable structures are essential.

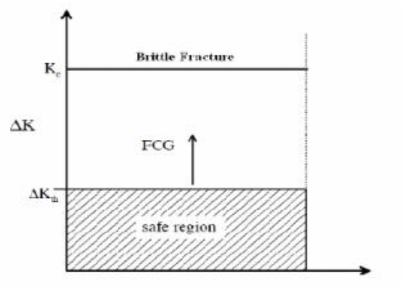

Fig.1.3 Schematic of ΔK Plotted Against K_{max}, Used To Demonstrate the Philosophy of Damage Tolerant Design [37]

Optimal design (between weight and fatigue criteria) of high-performance lightweight structures requires service loads to be just within safe limits. For fatigue loading, it is advantageous for ΔK (service loading) to approach, but does not exceed ΔK_{th}. Such a design criterion requires an appropriate value for ΔK_{th} and a good understanding of the variables that, influence threshold FCG. Any variation of ΔK_{th} is potentially dangerous.