Chapter 2

Literature review

2.1 Problems of Welding Aluminium Alloys

Majority of aluminium alloys can be welded by conventional arc welding processes like gas metal arc welding (GMAW or MIG), Tungsten Inert gas welding (TIG) as well as high energy processes like laser-beam, and electron-beam welding. Fusion welding of aluminium alloys possess certain difficulties because of the presence of tenacious oxides, high thermal conductivity, a high coefficient of thermal expansion, solidification shrinkage almost twice that of ferrous alloys, relatively wide solidification temperature ranges, high solubility of hydrogen when aluminium is in the molten state, and weld porosity. Proper plate surface, edge cleaning, the need for special filler wires, and weld pool shielding used in an inert gas atmosphere are usual practices when fusion welding aluminium alloys. Gas porosity is relevant to all alloys, but heat treatable Al-alloys such as the 2xxx, 6xxx, and 7xxx series, are more crack sensitive, and thus more difficult to fusion weld as per Cam et.al and Leinert et.al because these cannot withstand the contraction stresses generated when the weld metal solidifies [13,40] and cools. Cracking can occur in aluminium alloys because, of high stresses generated across the weld due to the high thermal expansion, and subsequent contraction upon solidification. Traditional methods of joining like riveting is being used because of the difficulty faced while welding aluminium alloys. FSW which is a novel method of joining difficult to weld aluminium alloys can be used to build aircraft structures.

2.2 Welding Al-Zn Alloys

Aluminium alloys have traditionally been used in aerospace structures. Aluminium alloys are known for their light-weight, and toughness which makes them ideal for use in aerospace structures. Aluminium Zinc alloy AA7075-T6 is the new age material being used in the construction of aero external tank, and other aerospace applications for its attractive combination of low density, high specific modulus, and excellent fatigue, and cryogenic properties.

Aluminium alloy structures used in aerospace applications are subjected to different kinds of high stress loading during takeoff, landing, supersonic speed maneuvering, and extraordinarily high gravitational forces. Cyclic loading and sudden overloads produce extremely high stresses on the wing structure.

2.3 Friction Stir Welding (FSW)

FSW is a thermo-mechanical solid state joining process i.e. no bulk melting of the base metal occurs during welding. The process was developed and then patented [70]. Mechanisms of heating and forging are readily identified in FSW.

The tool with a profiled surface is plunged until a portion of the tool shoulder comes in contact with the top surface of the work-piece. The penetration depth is determined by setting an axial force for controlled FSW machines or by estimating the plunge depth for position controlled FSW machines. The level of penetration is dependent on the composition of the alloy, material thickness, and rigidity of the welding machine. The heat produced by friction results in a reduction of flow stress of the work-piece material in the immediate vicinity of the tool. The tool is then traversed along the joint between the work-pieces. Often, the tool pin possesses a special profile, which when rotated enables horizontal as well as vertical movement of the thermally softened material. The softened material is then, forced to flow by the forward motion of the tool from the front to the back of the pin where it cools and consolidates, [78]. A schematic of the process of FSW is presented in Fig. 2.1.

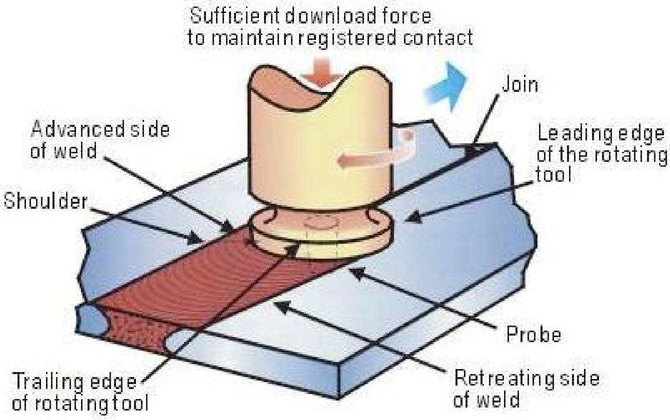

Fig. 2.1 FSW Depicting a Plunged and Rotating Tool Traversing the Work Piece [9]

Shortly after the invention, and subsequent patenting of FSW by TWI, [69] the process was systematically examined for the welding of various aluminium alloys with material thickness ranging between 1.2 mm and 10 mm. FSW tool development for aluminium alloys up to 6mm thickness proved so successful that the technology has been used for a number of major industrial applications. These applications include the fabrication of the Space-Shuttle external fuel tank for NASA/Lockheed Martin. Delta rocket fuel tanks and T45 undercarriage doors for Boeing have also used this fabrication technique. Further applications include heli-decks, bulkheads, the decks of ships in the ship building, and maritime industries as well as many applications in the aerospace, and to a lesser extent in the automotive industry, particularly where structural welds in high strength aluminium alloys, [9].

The process of FSW has demonstrated a number of advantages over competing, and conventional arc fusion welding processes. This is because of the exceptional properties, the hot forged friction-stir-welded joint delivers. Some of the advantages are derived from the fact that:

1. FSW occurs with the work piece material in the joint zone remaining in a solid state. Hence there is no bulk melting, thereby eliminating the problems associated with hot cracking or porosity development in the weld. Aluminium alloys have demonstrated a tendency to hot crack when the severity of deformation is too great.
2. The process produces lower levels of distortion in the work pieces compared to fusion welding as the material remains in a solid state and temperature generated are thereby very much reduced for FSW when compared to fusion welding.
3. No filler wire or shielding gas is required when FSW of aluminium, and its alloys.
4. No fume, no spatter, and no UV radiation are produced during FSW, therefore, the process can be considered environment friendly.
5. FSW uses readily available machine tool technology, and as such is easily automated thus, reducing the need for highly skilled operators.
6. FSW can be used in any orientation. The work piece material remains in a solid state throughout the joining process.
7. No special edge or joint preparation is required.
8. The FSW process produces a weld with exceptional mechanical properties, which for joining processes aluminium alloys equal or exceed those obtained by competing.

9. FSW can be used to join dissimilar, and difficult to weld materials. Apart from aluminium, industrial materials which have been shown capable of being friction-stir-welded include zinc, lead, copper, magnesium, titanium, and steel. Limitation

Rigid clamping of the work piece is seen as a limitation of the process. Until now, the work piece has always been fixed to a backing bar or anvil through mechanical connections, and clamping devices like screws, and U-bolts etc. Difficulty in automating the clamping process forces intervention of an external operator during mounting, and dismounting of the work piece. A vacuum operated clamping system reduces the setup time considerably but, it does not solve the problem as an operator is still necessary to ensure correct fit up. Rigid clamping is required to overcome high axial/forging forces. This means that, relatively robust machines are required thus limiting portability of the process. Another disadvantage of the FSW process is that a hole is left by the pin at the end of each weld. This hole in most cases is not desired because a void is left in the region of the weld joint, which means that this section at the end of the work piece cannot be used. Tools such as the retractable pin tool however, have demonstrated a methodology to overcome this problem [9]. Extensive research has been conducted in developing the FSW process for the aluminium alloys used in aerospace applications. However, the fatigue crack propagation behaviour of the friction-stir-welded Al-7075 alloy has not been reported in the literature. The future launch vehicles, which will have to be reusable, mandate the material to have good fatigue properties.

In welded joints cracks are generally initiated due to fatigue loading, and the crack propagates with periodic cyclic loading. Crack growth data of welded structures under fatigue load is necessary for the application of fracture mechanics methods to evaluate the residual life of welded structures. From the fatigue crack growth data it is possible to take a decision whether a crack needs to be repaired or the whole structure needs to be replaced. Therefore, the motivation for this work is to investigate fatigue crack growth behaviour for FSW Al-7075-T6 joints both experimentally and numerically under constant and variable amplitude conditions.

2.4 Microstructural Features

The solid-state nature of the FSW process combined with its unusual pin-tool, and asymmetric nature, results in a highly characteristic microstructure. While some regions are common to all forms of welding, some are unique to the technique. While the terminology is varied the following is representative of the consensus.

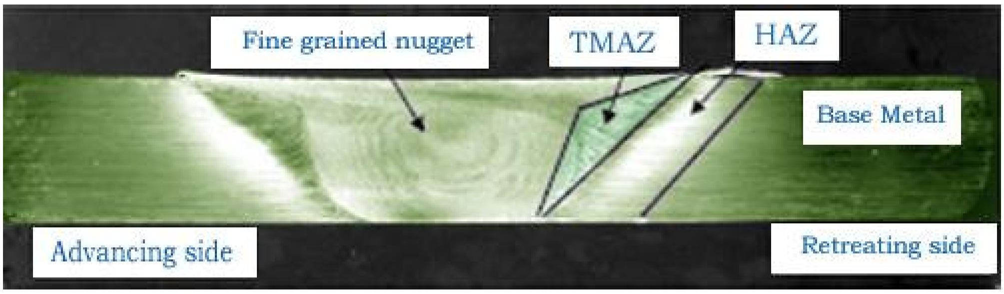

Fig. 2.2 Cross- section view of the FSW regions [38]

The stir-zone (also nugget, dynamically re-crystallised zone) in Fig. 2.2 is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir-zone are roughly equiaxed, and often an order of magnitude smaller than the grains in the parent material. A unique feature of the stir-zone is the common occurrence of several concentric rings which has been referred to as an "onion-ring" structure. The precise origin of these rings has not been firmly established, although variations in particle number density, grain size, and texture have all been suggested. The flow arm is on the upper surface of the weld, and consists of material that is dragged by the shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side. The Thermo-

Mechanically-Affected-Zone (TMAZ) shown in Fig. 2.2 occurs on either side of the stir- zone. In this region the strain and temperature are lower, and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir-zone the microstructure is recognizably that of the parent material, although significantly deformed, and rotated. Although the term TMAZ technically refers to the entire deformed region it is often used to describe any region already not covered by the terms stir-zone, and flow-arm. The 'Heat-Affected-Zone' (HAZ) shown in Fig. 2.2 is common to all welding processes. As indicated by the name, this region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure, is thermally unstable In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties.

2.5 Theory and Mechanisms of Fatigue Failure

AI-Zn alloys exhibit an extremely prominent role of crack-tip shielding, which largely accounts for their unique crack propagation behaviour. The specimen orientation is seen to have a strong effect on the fatigue crack- growth behaviour, with the lowest fatigue threshold obtained.

The stress intensity factor, K, is used in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load. It is a theoretical construct usually applied to a homogeneous, linear elastic material and is useful for providing a failure criterion for brittle materials, Intrinsic mechanisms are defined as those which promote crack extension via processes at or ahead of the crack-tip, while extrinsic mechanisms operate behind the crack- tip, and typically retard crack-growth.

2.6 Intrinsic and Extrinsic Mechanisms

Resistance to crack extension results from a competition between two classes of mechanisms (Fig. 2.3). Crack-growth is promoted ahead of the crack-tip by intrinsic microstructural damage mechanisms, and impeded by extrinsic mechanisms acting primarily behind the crack-tip, which serve to screen the crack-tip from the far-end driving force. In metals, intrinsic damage mechanisms under cyclic loading typically involve blunting, and re-sharpening of the crack. Extrinsic shielding mechanisms conversely, result from the creation of inelastic zones surrounding the crack-wake or from physical contact between the crack surfaces via wedging, bridging, sliding or combinations thereof, [64]. Intrinsic mechanisms are an inherent property of the material, and thus are active, irrespective of crack size or geometry. They control driving forces (or stress intensities) necessary to initiate cracking.

Extrinsic mechanisms, conversely act in the crack-wake, and are thus dependent on crack-size and specimen-geometry. Moreover, since extrinsic mechanisms have little effect on crack-initiation the microstructural factors affecting crack-growth (when cracks are large and possess a fully developed wake) may be quite different from that affecting crack initiation (when cracks are small and possess no wake). Dominant toughening mechanisms in ductile materials are intrinsic e.g. mobile dislocation activity and the associated crack-tip plasticity (although under cyclic loads extrinsic mechanisms play a critical role in the form of crack-closure). In contrast, brittle materials are invariably toughened extrinsically. As a short crack grows under constant load the crack-tip stress intensity factor increases, which leads to a change in crack propagation mode. At low stress intensities, fatigue cracks propagate along slip b, and emanating from the crack-tip. This mode of crack growth is called "Stage I", and is characterised by rough and faceted crack surfaces [64]. Higher closure levels associated with rough crack paths have been suggested as the cause of FCG threshold, [19]. As ΔK increases, the number of active slip-planes increase leading to smoother crack surfaces. This crack propagation mode, characterised by relatively smooth but striated crack surfaces, is called "Stage II" crack growth. Short fatigue cracks subject to increasing ΔK generally graduate from Stage I to Stage II FCG when the crack-tip plastic zone becomes larger than a typical grain.

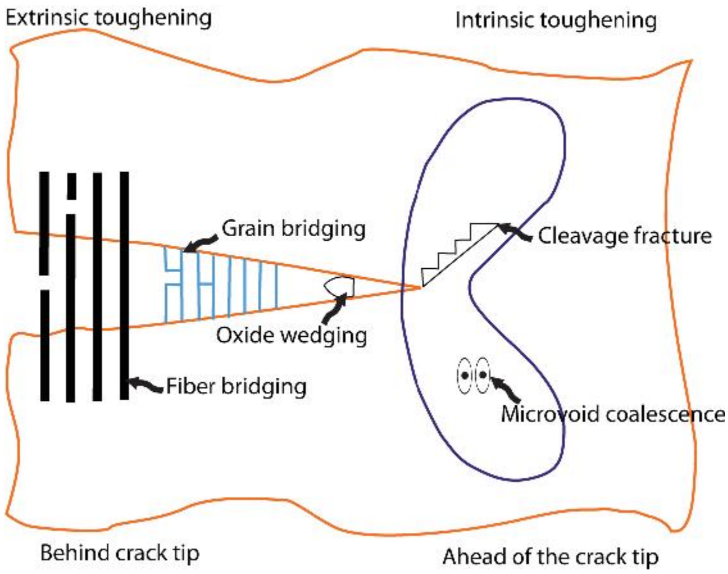

Fig. 2.3 Comparison of (a) faceted Stage-I and (b) striated Stage-II crack paths [45]

During long crack threshold, this transition occurs in reverse (from Stage II to Stage I) as ΔK is decreased. Stage-I and Stage-II fatigue crack-paths are shown schematically in Fig. 2.3 and 2.4. A rough and faceted Stage I crack is illustrated in part (a). While a (relatively) smooth, and striated Stage II crack is shown in part (b). Load ratio effects associated with microstructure are not limited to Roughness Induced Crack Closure (RICC). For example, crack-tip damage during fracture and FCG at elevated Kmax occurs about microstructural features, e.g. particles and dispersoids

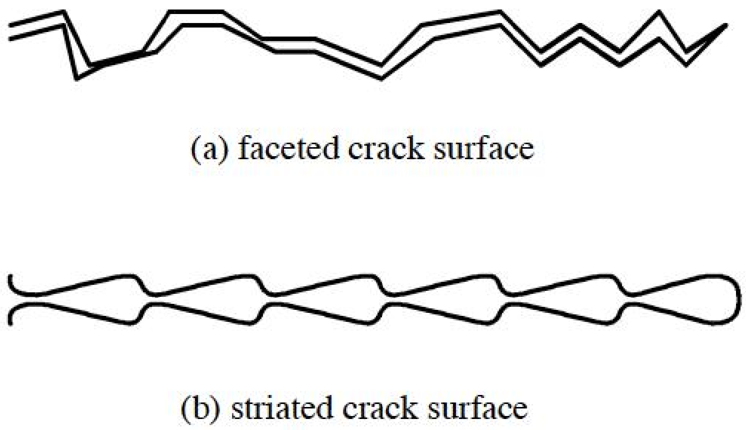

Fig. 2.4 Schematic Illustration of Mutual Competition between Intrinsic Mechanisms of Damage/Crack Advance, And Extrinsic Mechanisms of Crack-Tip Shielding involved in Crack Growth [34]

2.7 Crack-Growth-Rates

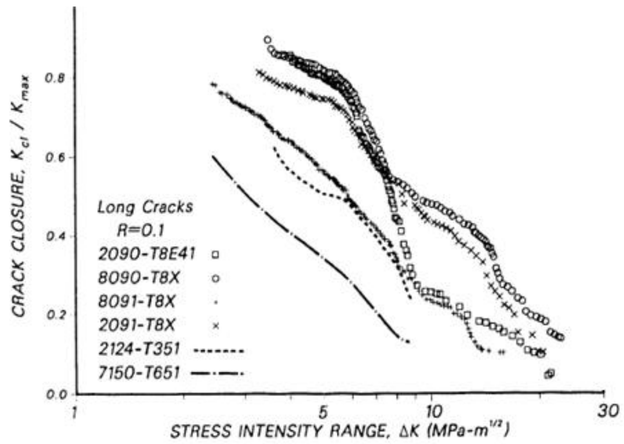

Fig.2.5 Crack Closure Levels for Long Cracks in Commercial AL-7xxx Alloys When Compared To Conventional High Strength Aluminium Alloys at R = 0.1 [64]

Constant-amplitude long-crack fatigue behaviour is generally determined with fracture-mechanic type geometries, The Al-Zn alloys can be seen to display consistently slower crack velocities over the entire spectrum of growth rates, except perhaps at near-threshold levels compared to Al-7xxx. Such behaviour is attributed primarily to their higher crack-closure levels (Fig. 2.5) which, unlike traditional alloys, remain significant even at higher growth rates; in Al 7xxx, for instance, Kc/Km ratios remain over 0.1 for K levels as high as 7-8

2.8 Crack Closure Mechanisms

The concept of fatigue crack closure was a conceptual breakthrough for understanding load ratio effects on FCG. Closure occurs because fatigue cracks grow through the plastic strain field generated at the crack-tip, [19]. Once in the crack wake, plastic deformation partially fills the crack mouth causing premature contact, i.e. crack closure.

Closure due to contact of rough crack surfaces was first described in [1,60 & 72]. This closure mechanism, called Roughness Induced Crack Closure (RICC), occurs when misaligned rough crack surfaces contact during unloading.

2.9 Numerical Analysis

In recent years, with the development of powerful computing facilities, Finite Element (FE) analysis methods have been applied to the simulation of structural behaviour using commercial FE software packages. However, for general usage, especially in routine structural integrity assessments, the simplified state-of-the-art methods are much more popular than full step-by-step elastic–plastic analysis. The crack growth rate was measured during constant amplitude fatigue testing on un-welded, as-welded, and weld repaired specimens of 5083-H321 aluminium alloy [76]. A 3-D finite element analysis was conducted to determine the stress intensity factors for different lengths of crack, taking into account the three-dimensional nature of the weld profile. The effects of crack-closure due to weld residual stresses were evaluated by taking measurements of the Crack-Opening-Displacements (COD), and utilised to determine the effective stress intensity factors for each condition. It was found that crack growth rates in welded plates are of the same order of magnitude as those of parent material when effective stress intensity factors were applied. The weight function for edge cracks proceed from the weld toe in a T-butt welded joint has been derived by using the crack opening displacement function [25]. The weight function makes it possible to study efficiently the effect of weld profile parameters, such as the weld toe radius, and weld angle, on stress intensity factors corresponding to different stress systems. It has been found from experience that most common failures of engineering structures such as welded components are associated with fatigue crack growth caused by cyclic loading. Engineering analysis of fatigue crack growth is frequently required for structural design, such as in Damage Tolerance Design (DTD) and residual life prediction when an unexpected fatigue crack is found in a component of engineering structure. For analysis, the fatigue life of welded structures can be divided into two parts crack initiation phase, and propagation phase. Fatigue crack propagation behaviour is typically described in terms of crack growth rate or crack length extension per cycle of loading (da/dN) plotted against the stress intensity factor (SIF) range (ΔK) or the change in SIF from the maximum to the minimum load.

The central portion of the crack growth curve is linear in the log-log scale. Linear Elastic Fracture Mechanics (LEFM) condition essentially deals with crack propagation in this region, which is commonly described by the crack growth equation [58], and popularly known as the Paris law, as given below.

Where C and m are material dependent constants and (ΔK) is the range of SIF. It should be noted that Paris law only represents the linear phase (region II) of the crack growth curve. As the stress intensity factor range increases approaching its critical value of fracture toughness (Kc), the fatigue cracks growth becomes unstable and much faster than that predicted by Paris law. The following relationship [22] is for describing region II, and III together

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R)K_c - \Delta K} \qquad 2.1$$

Where R is the stress ratio, equal to $\pm_{min}/\pm_{max}$ that the above relationship accounts for stress ratio R, effects while Paris's law assumes that da/dN depends only on ΔK. Based on the above relationship, fatigue crack propagation life can be predicted by integrating both sides of these functions if a suitable SIF solution is obtained. Since, weld geometry conditions may differ in various weld joints, traditional empirical relations become invalid in some cases, and new models may have to be created for local stress distribution, and accurate stress intensity factor calculation. In line with the traditional da/dN testing approach, nearly all the present da/dN data for welded joints were obtained by using bead removed specimens, for which classical two-dimensional solutions for stress intensity factors become applicable. Using da/dN data obtained from bead removed specimens for fatigue design or fatigue life prediction on as-welded joints may lead to error conclusions. Therefore, determination of accurate stress intensity factor solutions for the correct weld geometry conditions is of practical significance in structural design, and fatigue life evaluation of welded structures.

2.10 Finite Element Simulation of Fatigue Crack Growth

Many researchers have in the past used numerical approaches for fatigue crack propagation. In this regard, the works discussed in [47 & 49], are noteworthy and path-breaking. A general trend of the numerical approach in this field over the past 25 years can be inferred from those references. A crack-tip node–release scheme was first discussed [53], in which a change in the boundary condition was characterised as crack growth. This was achieved by changing the stiffness of the spring elements connected to boundary nodes of a finite element mesh. Before Newman's work, investigators changed boundary conditions of the crack-tip node directly to obtain a free or fixed node. When the crack-tip is free, the crack advances by an element length. The approach Newman used to change boundary conditions was to connect two springs to each boundary node [49]. To get a free node, the spring stiffness in terms of modulus of elasticity was set equal to zero, and for the fixed ones it was assigned an extremely large value (about 120 GPa) which represents a rigid boundary condition. The investigated fatigue crack closure by the finite element method is discussed [47]. Their model for the elastic-plastic finite element simulation of fatigue crack growth used a crack closure concept. They followed the node release scheme at the maximum load, and assumed that the crack propagates one element length per cycle. The fatigue crack closure using an elastic-plastic finite element model is studied [75]. The study is an extension of Newman's node- release scheme.

They used a truss element instead of a spring element, and released one node after each cycle of fatigue load. Recent use of the cohesive element approach has been reported in crack propagation simulations. Cohesive elements originate from the concept of cohesive zone, was first discussed [7 & 18]. The implementation of cohesive zone into numerical analysis takes the form of cohesive elements, which explicitly simulate crack process zone. The work is demonstrated successful with use of the cohesive element technique in 2-D cases [77]. In a cohesive element, the material separation process is described by the cohesive law, which defines the relation between crack surface traction, and surface opening displacement. The use of initial elastic and, then an exponentially decayed cohesive law (the Smith-Ferrante law). The concept of the interface element for the strength analysis of a joint between dissimilar materials was first discussed [44, 2]. They also used it for the calculation of the strength of peeling of a bonded elastic strip, and the fracture strength of a centre cracked plate under static load. This was further used for simulation of hot cracking, push-out test of fibers in matrix, ductile tearing, and dynamic crack propagation under pulse load, and pre-stress condition [44] & [28]. Repeated cyclic load was not applied for fatigue crack propagation. Investigation in the use of cohesive theories of fracture, in conjunction with the explicit resolution of the near-tip plastic fields, and the enforcement of closure as a contact constraint, for the purpose of fatigue life prediction,[54]. In their finite element model the crack advances by shifting the near-tip mesh continuously. After every re-mesh, the displacements, stresses, plastic deformations, and effective plastic strains are transferred from the old to the new mesh.

This study is similar to cohesive model but in this model the element bonding strength and surface energy were used to set the criterion of crack propagation. Further the technique used in the finite element model was different from other models. It should be pointed out that, the past use of finite element analyses had certain shortcomings, and recent versions have tremendous improvements, and have removed many of these limitations. For example, to avoid numerical instability, schemes such as releasing the crack-tip node at the bottom of a loading cycle were adopted in certain studies, [77].

They did not consider element bonding stress, and surface energy, which were associated with crack formation, and extension. They also did not consider the material properties change during cyclic loads. They applied symmetric boundary conditions at the crack plane and also assumed that the crack can propagate only in symmetric planes.

LEFM principles can be used to evaluate the fatigue crack growth behaviour, and thus, to predict fatigue life of welded structures. In order to appropriately assess fatigue crack growth process in welded joints it is necessary to obtain accurate results for stress intensity factor solutions in the crack propagation phase. Generally the stress intensity factor for a crack in a welded joint depends on the global geometry of the joint which include the weld profile, crack geometry, residual stress conditions, and the type of loading. Calculation of the stress intensity factor, even for simple types of weldments, requires detailed analysis of the several geometric parameters, and loading systems. The two approaches that have mostly been used till now for assessing stress intensity factors for crack in weldments are weight function method, and the finite element method (FEM).

The numerical approach is based on basic weight functions applied for stress intensity factor calculation. The stress distribution, $\zeta(x)$ can be calculated by FE method. Weight function $m(x, a)$ have been derived in [11] & [51] for 2-D, 3-D model edge crack, and surface semi-elliptical crack in finite thickness plate, respectively. Based on the Buckner's weight function, creation of a semi elliptical crack model for the stress intensity factor calculation on butt weld joints considering all weld geometry parameters,[55]. Using this model, and Paris law, fatigue life of butt weld structure can be estimated. As a numerical approach, weight function methods require huge calculations, which is time consuming, and inconvenient for practical engineering applications.

The applications of the finite element methods to determine crack-tip stress field has developed rapidly in recent years. The method has great versatility as it enables the analysis of complicated engineering geometry, and three-dimensional problems. It also permits the use of elastic-plastic elements to include crack-tip plasticity. Basically, two different approaches can be followed in employing finite element procedures to arrive at the required stress intensity factor. One approach is the direct method in which K follows from the stress field or from the displacement field around the tip of fatigue cracks, [3]. The following equation (2.2) describes the calculation process for determining Mode I stress intensity factor solutions using crack-tip stress field.

$$K_I = \lim_{r \to 0} \sqrt{\pm \text{®}\, r} \tag{2.2}$$

The stress intensity factor can be inferred by plotting the quantity in square brackets against distance from the crack-tip, and extrapolating to r tends to 0. Alternatively, KI can be estimated from a similar extrapolation of crack opening displacement.

$$K_I = \frac{2\text{«}}{k+1} \lim_{r \to 0} \left[u \sqrt{\frac{2\text{®}}{r}} \right] \tag{2.3}$$

The constant *k* in Equation (2.8) is:

k = 3-4ν (plane strain)

k = (3- ν)/ (1+ ν) (plane stress)

Where μ is the crack opening displacement, m is the shear modulus, and ν is the Poisson's ratio. Equation (2.3) tends to give more accurate estimates of K1 than equation (2.2) because nodal displacement can be inferred with higher degree precision than stresses. The second approach for K calculation comprises some indirect methods in which K is determined via its relation with other quantities such as the compliance, about the elastic energy [24] or the J-integral, [63].

2.11 Weld Residual Stress (WRS) and Its Effect on Fatigue Life.

Weld residual stress (WRS) introduced by the welding process can come from the expansion, and shrinkage of weldments during heating, and cooling misalignment, and microstructure variation in weldments, and Heat-Affected-Zone (HAZ). Residual stresses in weldments have two effects. Firstly, they produce distortion, and second, they can be the cause of premature failure especially in fatigue fracture under lower external cyclic loads, [73]. WRS in friction stir welded components have been studied in [67] on Al-2195 specimens shown in Fig.2.6. There are tensile longitudinal stresses in the region of the weld. The presence of these stresses may have a negative effect on the fatigue, and crack propagation properties in this region. The residual stress component in normal direction appears to be quite high for a sheet of this thickness. The reason is most likely, a change in the unstrained lattice spacing in the heated weld region due to a change in the Cu concentration in the matrix in this heat treatable Al alloy.

Tensile residual stress can significantly decrease the fatigue properties on welded joints. On the other hand, compressive stresses on the surface of weldments introduced by post-weld treatment can significantly improve the fatigue properties of welded structures. Previous investigations have indicated that WRS also has significant effects on the fatigue crack initiation phase, and the early stage of crack propagation [56].

Investigation was done on fatigue crack growth behaviour in butt weld joint of Al-5456-H116 aluminium alloy and ASTMA 710 steel [41]. Crack closure levels were determined graphically using the upper tangent point, and non-subjectively by measuring the 2% deviation from the upper linear portion of P-COD traces. The experimental results showed that the da/dN curve, when using the effective stress intensity factor range, shifted to faster growth rates in welded plates compared to the base plate. Crack closure loads of up to 80% of the maximum load were measured in both Aluminium, and steel welded specimens.

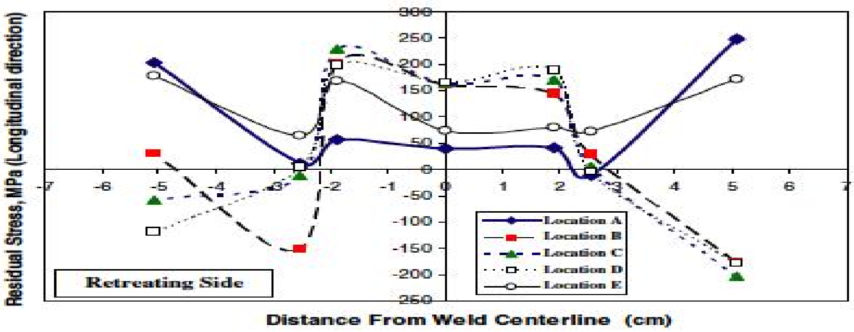

Fig. 2.6 Weld residual stress plot in a Friction stir welded Al-2195 specimen [67]

These closure levels were mainly created by the presence of weld residual stress (WRS). For stress relieved steel specimens, the fatigue growth rate shifted to rates equivalent to those of the base plates. It was concluded in the paper that applying effective stress intensity factor, taking into account of weld residual stress effects, results in more accurate estimations of fatigue life in welded joints [20]. The influence of residual stress in da/dN can be evaluated using the concept of effective stress intensity factor, which assumes that propagation occurs only when the crack is completely open. He also found that, the influence of residual stress leads to incorrect interpretation of fatigue crack growth rate measurements made in accordance with standard ASTM E-647.

2.12 Weld Defects and Welding Metallurgy

Weld defects are those imperfections or discontinuities produced in the weldments because of the weld process, such as porosity, lack of penetration, slag inclusions, incomplete fusion, misalignment, undercut, weld profile etc. These weld defects can significantly influence local stress field in the vicinity of welds when the welded component is subjected to cyclic fatigue load.

In most cases, weld defects lead to severe stress concentration, and thus accelerate fatigue crack growth. Studies conducted on the effects of lack of penetration (LOP), and lack of fusion (LOF) on the fatigue behaviour of Al-5083-0 double-V groove butt welds [65]. They concluded that LOP defects can seriously reduce the fatigue life of both types of weld, those with the reinforcement intact, and those with the reinforcement removed. Less than full length, inclined LOF defects were generally less serious than LOP defects. Sanders also reported that, the effects of internal discontinuities on fatigue performance of welds with reinforcements are minimal. The effect of weld reinforcement is so marked that only critical defects would affect the fatigue behaviour, and this is related to the loss of cross section area. Porosity only becomes a factor when the reinforcement is removed.

2.13 Materials for Aerospace Structures

2.13.1 Aluminium Alloy AA7075-T6

Rolled plates of 5 mm thick, AA7075-T 6 aluminium alloy base metal, were cut to the required size (300 mm 150 mm) by power hacksaw and milling. The microstructure of base metal (AA7075- T6 aluminium alloy) consists of acicular eutectic precipitates. From this investigation it was found that the joint fabricated at a tool rotational speed of 1400 rpm, welding speed of 60 mm/min, axial force of 8 kN, using the tool with 15 mm shoulder diameter, 5 mm pin diameter, 45 HRC tool hardness yielded higher strength properties compared to other joints. While it is possible to overcome the problem of weld solidification crack using suitable non-heat treatable aluminium alloy filler (for example, Al–Mg or Al–Si), the resulting joint efficiencies are unacceptably low Microstructure and fractographs. The investigated material, is an alloy of aluminium and zinc, which has undergone a T6 heat treatment.

The AA7075-T6 alloy research on the microstructural characteristics and mechanical properties of the friction-stir-welded joints, [42] concluded that FSW softens the joints of the heat-treatable aluminium alloys such as AA2024-T3 alloy and AA7075-T6 alloy because the strengthening precipitates dissolved and grew during the welding thermal cycle which resulted in the degradation of the mechanical properties of the joints.

The study considered the microstructural changes of AA7075-T6 alloy only at travel speed of 5 in/min and did not specify the reason for using 5 in/min as the travel speed for the weld [62].

Well defined micro structural bands which are the micro structural feature generally observed in FSW nugget region was the focus of the research. They concluded that, the onion ring banded structure was because of the nominal cylinders of the metal being extruded by the tool and shredding these sheets of metal during the rotation of the tool. The bands of distinctive hardness maxima and minima were observed in the HAZ. Though the authors have not investigated, they predicted that, these bands were due to the presence of the onion rings. Investigations performed, on the transverse cross-sections of the specimens of the FSW process of the AA2024 and AA7075 aluminium alloys revealed the formation of the elliptical “onion” structure in the centre of the weld [14].

The mechanical and microstructural properties of AA2024 and AA7075 aluminium alloys which were joined together by friction stir welding [15] were investigated. The rotating speed of the tool was 700 RPM while the welding speed was 2.67 mm/s. The AA7075 alloy was on the advancing side of the tool while the AA2024 alloy was on the retreating side. The authors concluded that AA2024 and AA7075 aluminium alloys were successfully joined by FSW and no superficial porosity or defects were observed in both weld top and rear surface. The tensile response, transverse to the welding direction, of the AA2024 and AA7075 joined by FSW was studied and the authors concluded that the tensile strength of AA7075-T6 is the highest (600 MPa).

The mechanical and microstructural behaviour of AA2024–AA7075-T6 aluminium alloy sheets joined by friction stir welding [14] were investigated. The resulted microstructure due to the FSW process was studied by employing OM and FESEM either on ‘as welded’ specimens and on tested specimen after rupture occurred. The main results revealed that the dissimilar AA2024 and AA7075 aluminium alloys in the form of 2.5 mm thick sheets were successfully joined by friction stir welding.. The specimens fracture surfaces after testing were deeply analysed by using a FESEM microscope, revealing the defects typology and location after the friction stirring process and the microscopic mechanisms occurred during high stress deformations and final failure.

Friction Stir Welding in 7xxx Series Aluminium alloys showed the effects of FSW on micro-structure of AA7075 aluminium alloy [62]. They stated that the technique, based on friction heating at the faying surfaces of two pieces to be joined, results in a joint created by interface deformation, heat, and solid-state diffusion. The weld was characterised by a recrystallised nugget having a 2-4 μm grain size. The dislocation density in the nugget was lowered from that in the parent metal; strengthening precipitates appear to have been solutionised during the welding process, with the larger ones re-precipitating on cooling. The process, thus, provided a method for joining difficult to weld aluminium alloy without introducing a cast microstructure.

AA7075 (Al–Zn–Mg–Cu) is a precipitation-hardened aluminium alloy widely used in aerospace applications due to its high strength to weight ratio. The rolled plates of 6mm thickness were machined to the required size (300mm × 150mm). In FSW process, the base metal properties such as tensile strength, ductility and hardness, control the plastic flow of the material under the action of rotating non-consumable tool.

The FSW process parameters such as tool rotational speed, welding speed, axial force etc, play a major role in deciding the weld quality. Macro structural analysis was done to check the weld quality (defective or defect free). Specimens were etched with Keller's reagent to reveal the macrostructure. Finding the most effective parameters on properties of friction stir welds as well as realising their influence on the weld properties were major topics for researchers. The influence of some of important parameters such as axial tool pressure (P), rotational speed (R) and traverse speed (T) on weld properties were investigated. In all the above investigations, the FSW parameters were being selected by trial and error to fix the working range to get defect free welds.

Based on the above parameters the material flow rate can be identified and it can facilitate defect free welds.