THE INFLUENCE OF FATIGUE CRACK INITIATION BEHAVIOUR OF FRICTION STIR WELDED JOINTS ON THE DESIGN CRITERIA

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Abstract

Friction stir welding is a new joining methodology which can be applied in the aerospace industry. However, new joining methods require new design principles, which are based upon the behavior of the joint. Extensive mechanical and fatigue research resulted in new insights in the behavior of friction stir welds. This paper describes how the new insights lead to the design principles on which the design of a damage tolerant fuselage structure is based.

1 Introduction

Friction Stir (FS) welding is a fairly new joining technology with promising characteristics for the aerospace industry. Advantages of the application can be found in two areas, i.e. the structural weight and complexity, and production costs.

Application of FS welds in a fuselage will not lead to a rivet free structure, because other elements are still riveted. Besides, FS welding might not be applicable for all joints in the structure. Therefore, design rules are required which describe how to deal with rivets in the neighborhood of an FS weld. Moreover, the design rules should describe whether a FS weld can be applied to a certain joint in the structure or not.

The design of an aircraft structure is nowadays based on the damage tolerant philosophy, which means that a structure must be able to fulfill its task even when a damage is present. In general, damages are repaired using a riveted repair patch. For the maintenance crew it is impossible to know exactly where an FS weld is located because the welds are not visible after welding. Therefore it is possible that the rivets of a repair patch are placed in an FS welded joint. A designer should recognize the scenario of a rivet in the FS weld and use the lowest properties to evaluate the design.

In general, design rules are based upon understanding of the material and structural behavior and experimental data. To obtain the fatigue initiation behavior of FS welded joints, an extensive test program was performed using FS welded centre hole specimens [1]. The goal of this research was to investigate the influence of the location in the weld on the fatigue initiation life. Moreover, the weld was tested in three directions, longitudinal (parallel to weld), oriented in 45º and transverse (perpendicular to the weld). From this research it was concluded that the residual stresses have a significant influence on the fatigue crack initiation properties.

To understand the mechanical behavior of the FS welds, other experiments were conducted to obtain detailed information on the local yield strength and the residual stress profiles [2]. The results of those tests, gave valuable information which is used in this paper to describe the influence on the rivet stability.

This paper describes how the mechanical and fatigue behavior of a FS weld affects the design principles of a damage tolerant structure. The focus is on a fuselage structure, because that is a challenging structure with some typical load cases.

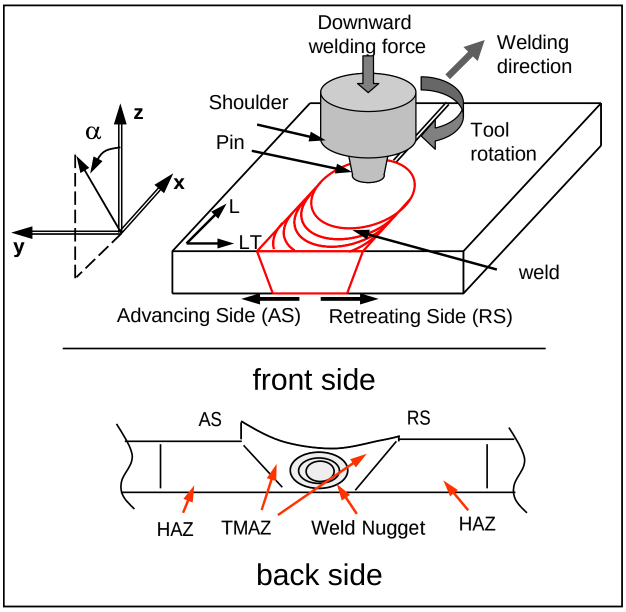

Fig. 1. FS weld tool, definition of axes and weld zones

2 Friction Stir Welding

The FS welding tool consists of a non-consumable rotating cylinder with a 'pin' at the centre of the lower circular surface, the 'shoulder' (Fig. 1), which is pushed into the work piece and moves through the joint. The heat, generated by friction softens the aluminum allowing the pin to stir the material of two parts together. In general, three zones can be distinguished in the weld (Fig. 1), the stirred zone or weld nugget, the Thermo-Mechanically Affected Zone (TMAZ), and the Heat Affected Zone (HAZ). All three zones have a different thermal and/or mechanical history. The welds for this research were produced at EADS in Munich with an ESAB FSW machine. A tool with a shoulder and pin diameter of 13 and 5 mm respectively was used to produce the welds. Due to the rotation of the FSW tool in combination with the traverse speed of the specimen, the difference in speed between the tool and the specimen is higher on one side compared to the other. These sides are defined as the Advancing Side (AS) and the Retreating Side (RS) respectively (Fig. 1). Prior to welding, the oxide layer was removed from the edge by a wire brush and cleaned with acetone. The sheets were clamped and a sheet of highly oxidized carbon steel was placed below the specimens to prevent them being welded to the table. All welds were performed parallel to the rolling direction of the aluminum, because this is the common orientation of a longitudinal joint in an aircraft fuselage.

2.1 Yield Strength Profiles

The aluminum alloys used for fuselage structures receive their high strength properties from precipitation hardening. However, the type of precipitation hardening is fully dependent on the aluminum alloy. Some alloys, like AA2024-T3, are natural aged which means that the precipitation process happens naturally at room temperature. Other alloys, like

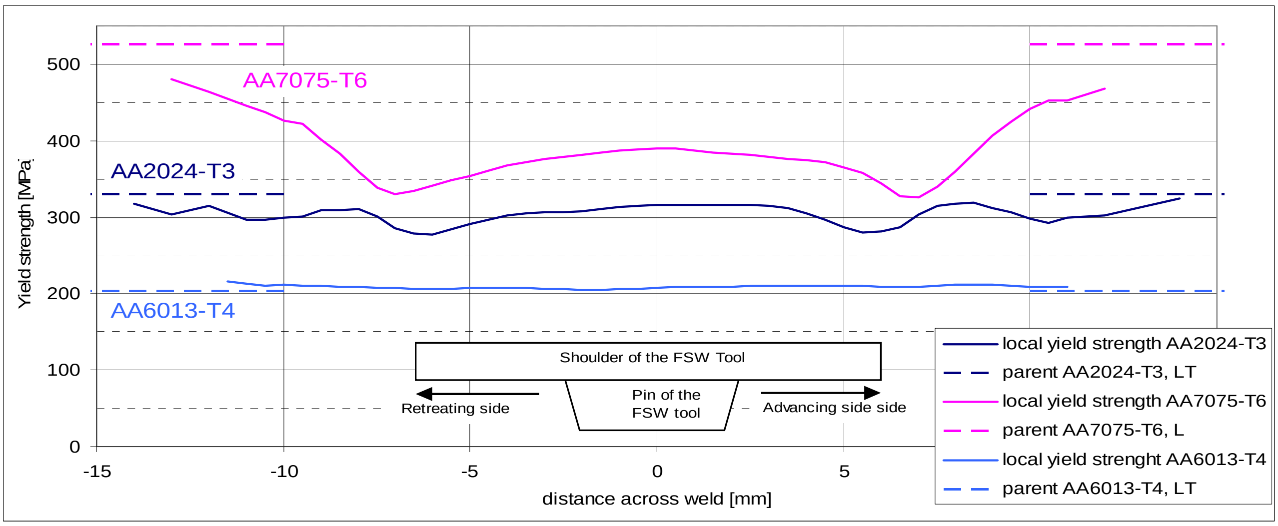

Fig. 2. Yield strength profiles for FS welded AA2024-T3, AA7075-T6 and AA6013-T4

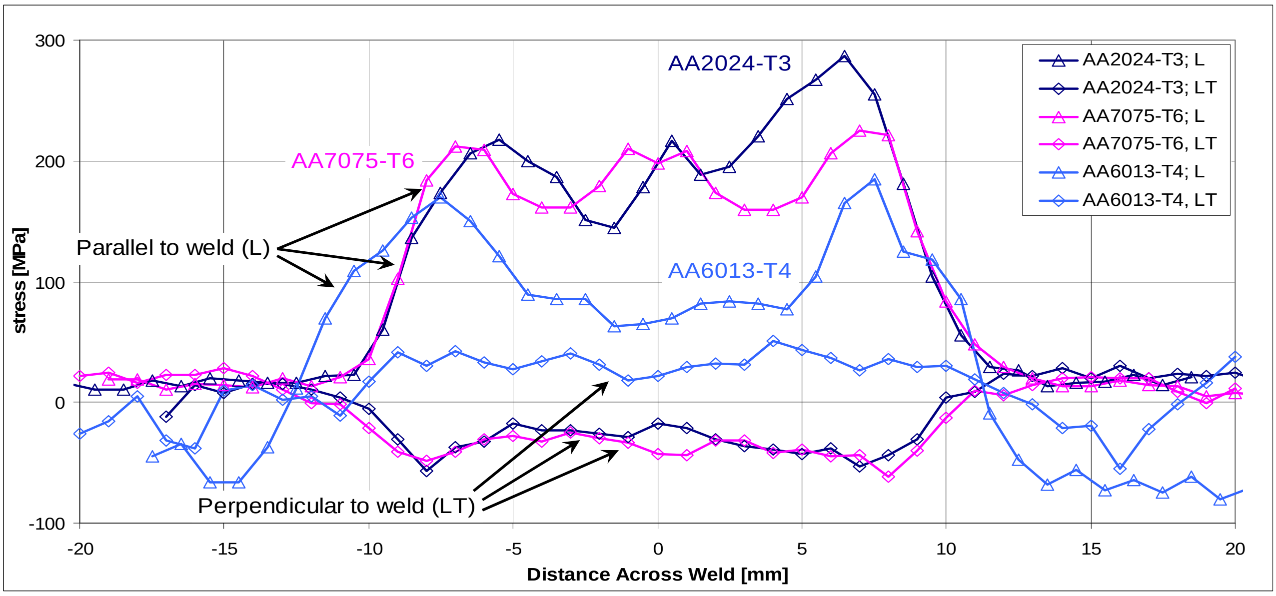

Fig. 3. Residual stress profiles in L (parallel to weld) and LT (perpendicular to weld) direction for FS welded AA2024-T3, AA7075-T6 and AA6013-T4

AA7075-T6, can only retrieve the high precipitation strength by artificial ageing which requires a heat treatment. In general, the yield strength is reduced locally by FS welding, but the reduction is highly dependent on the aluminum alloy and its precipitation process. If an alloy is artificially aged, the reduction in yield strength is permanent without an additional heat treatment. On the other hand, a naturally aged alloy is capable of regaining the high strength properties simply by letting the FS weld rest for a period of time. However, the mechanical properties of artificial aged alloys are in general higher than the mechanical properties of natural aged alloys.

Because the yield strength has a large influence on the mechanical behavior of an FS weld in a structure and on the fatigue crack growth properties, experiments were conducted to measure the local yield strength [2]. To obtain the local yield strength, digital image correlation was used successfully, resulting in yield strength profiles of FS welded AA2024-T3, AA7075-T6 and AA6013-T4 (Fig. 1). From those three alloys the reduction in yield strength is the highest for AA7075-T6, 30 %, mainly because this alloy is artificial aged and has only minor natural ageing capabilities. AA2024-T3 has natural ageing capabilities, but it is dependent on the local heat input received by the material, because different precipitation systems are active in the alloy. AA6013-T4 can natural age completely after welding, resulting in no reduction of yield strength.

2.2 Residual Stress Profiles

During FS welding the sheet material is heated up and cooled down in a short period of time. Moreover, the material is highly deformed, especially in the nugget and the TMAZ. Both processes result in residual stresses in the FS weld. The residual stresses in FS welded material used for this research, i.e. AA2024-T3, AA7075-T6 and AA6013-T4, were measured by the company Proto Manufacturing Ltd. using X-ray diffraction technology [2-4]. The results showed high residual tensile stresses parallel to the weld, but low and negligible residual stresses perpendicular to the weld (Fig. 3). For all three FS welded alloys the trend in the residual stress profiles are comparable. All measurements in L-direction showed two peaks at a distance of 7.5 mm from the weld centre, which is at the edge of the FS welding tool. Besides, the magnitudes of the residual stress profiles are different for each alloy, but the differences are smaller than expected from the difference in yield strength of the alloys. In terms of yield strength, the residual stresses can

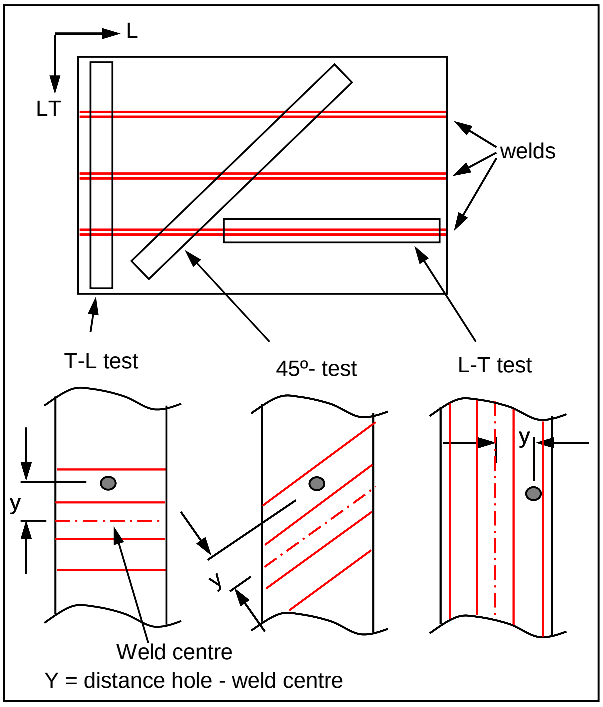

Fig. 4. Orientation of FS welds in the fatigue test specimens

go up to 85 % of the yield strength, depending on the alloy.
The residual stress fields in LT-direction show a small valley at 7.5 mm from the weld centre.

2.3 Fatigue Crack Initiation Behavior

The fatigue initiation test program was conducted to investigate the influence of the different FS weld zones on the fatigue initiation behavior [1]. To obtain this information, centre hole specimens were used with different orientations of the FS weld (Fig. 4). The holes had a diameter of 1 mm to obtain the fatigue initiation properties of only one location in the FS weld. Each specimen contained three test locations to reduce the test time. Only FS welded AA2024-T3 was fatigue tested.
The results showed a high dependency of the fatigue initiation properties on the orientation of the weld. The difference found for the fatigue initiation properties at the different locations in the FS weld, are small for the T-L tests (Fig. 5), while the differences are significant for the L-T tests (Fig. 6). The explanation for this behavior is found in the residual stresses which are highly orientation depended. Besides, the minimum fatigue initiation properties were not found at

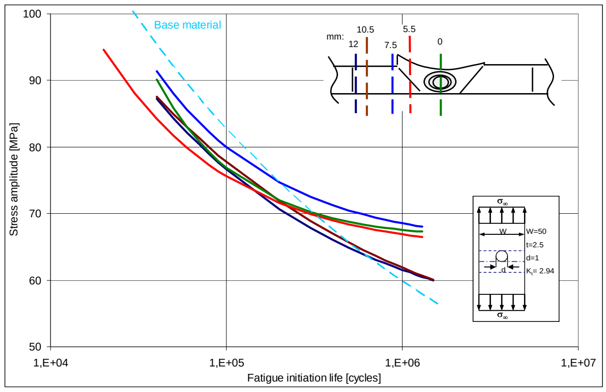

Fig. 5. S-N$_i$ curves of FS welded AA2024-T3 for different locations in the weld, load is perpendicular to weld T-L direction [1]

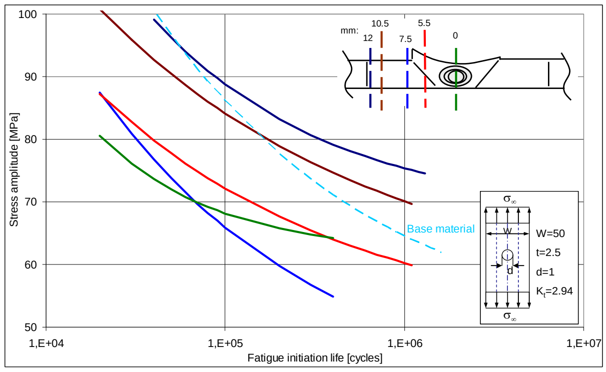

Fig. 6. S-N$_i$ curves of FS welded AA2024-T3 for different locations in the weld, load is parallel to weld; L-T direction [1]

the weld centre, but at 7.5 mm from the weld centre. 7.5 mm from the weld centre corresponds to the locations where the residual stress peaks are located (Fig. 3).
For both the T-L and the L-T test direction, reference tests were performed on un-welded specimen with the same geometry as the welded specimens. The reference curves show that the difference is not large between the fatigue initiation properties of the welded material and the base material in T-L direction. In L-T direction the fatigue initiation properties are slightly better at the edge of the FS weld, but that is due to the local compressive residual stress at that location.

3 Fuselage structure

The primary function of the fuselage is to carry the payload, cargo or passengers, and to maintain an environment in which passengers

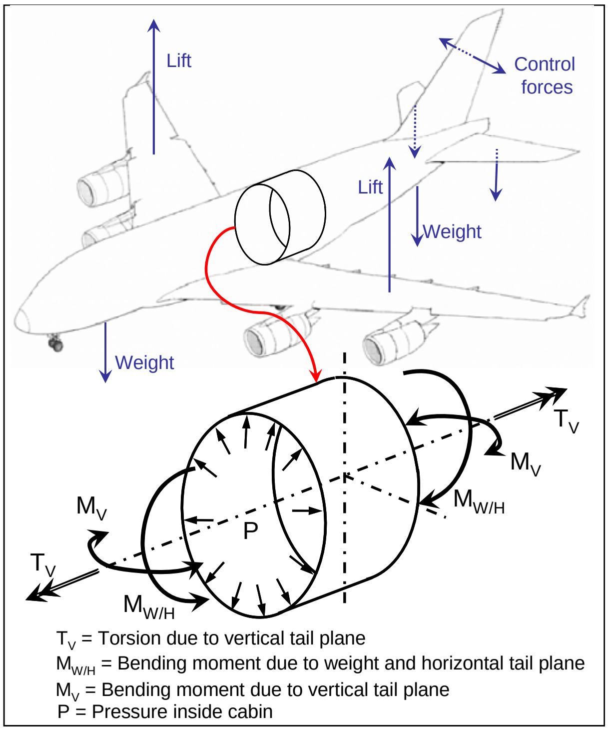

Fig. 7. Loads on a fuselage section

are comfortable. To fulfill these functions the fuselages of commercial aircrafts are pressurized and the temperature is controlled by the air conditioning system. The pressure of the fuselage introduces loads on the fuselage structure, which is explained in paragraph 3.1.
The air-condition in the fuselage in combination with the outer temperatures result in condense water which flows to the lower areas of the fuselage. For this research the corrosion properties of an FS weld are not considered. However, several studies can be found in the literature about the topic of corrosion in an FS weld [5-7].
Fuselage structures are nowadays designed according to the principle of damage tolerance. A damage tolerant design is able to continue its operation even when the structure is damaged. Moreover, a damage may never growth to a critical size endangering the operability of the aircraft before the damage could be detected during inspection. This sets criteria for not only the behavior of the structure, but also for the detectability and the repairability of the structure.

3.1 load cases in the fuselage

The loads in the fuselage structure are produced mainly by three cases, pressurization of the fuselage, the bending moment due to the weight of the fuselage, the torsion and bending loads due to the control surfaces at the tail planes (Fig. 7). It depends on the diameter and length of the aircraft how large the contributions of the different loads are, but in general, the loads due to the pressurization of the fuselage are the largest. With equation 1 and 2 the stresses in the fuselage skin due to the internal pressure are calculated [8]. These equations show that for a pressure vessel, the circumferential stresses are twice as high as the longitudinal stresses. Therefore the structure is mainly dimensioned based on the circumferential stress. When the circumferential stresses are dominant for the design, this means that the longitudinal joints will be subjected to the highest stress levels.
Both stresses are dependent on the pressure (P), the radius of the vessel (r) and the skin thickness (t).

$$\sigma_{\theta,Circumferential} = \frac{\mathrm{P} \cdot r}{t} \qquad (1)$$

$$\sigma_{z,Longitudinal} = \frac{\mathrm{P} \cdot r}{2t} \qquad (2)$$

Due to the bending moment of the weight, the longitudinal stress is higher in the upper skin than in the lower skin of the fuselage. Therefore, the upper part of the fuselage is dimensioned for tensile strength while the lower part is dimensioned for compression stability. The less critical design for tension in the lower part of the fuselage explains why laser beam welding of the stringers to the skin is only applied in this area of the Airbus A318 and A380 [9].
The whole fuselage is loaded in shear due to the torsion moment from the vertical tail plane. Especially in the skin at the side of the fuselage, the shear stresses may become dominant.

3.2 Damage sources for a fuselage

Several damage sources are known for commercial aircrafts which can be subdivided in two categories; handling, and operational damages. Damages due to handling are in general impact damages of trucks or stairs which approach the aircraft on the platform to load and unload passengers and cargo. Therefore handling damages occur mainly around doors in the lower part of the fuselage.

Operational damages, like bird impact, runway debris impact, lightning strike, etc., are mostly limited to certain locations of the fuselage. For instance, bird impact will only occur at the front side of the fuselage, while lightning strike occurs at the upper side of the fuselage (see illustrations in [10]).

The worst case scenario which is considered for a damage tolerant structure is the case in which a fan blade separates from the engine and hits the fuselage. This scenario led to the two bay crack criterion in which it is considered that one frame is cut through and that a fracture of significant length exists. The two bay crack criterion states that the fracture may not cross the surrounding intact frames and that the structure must be able to continue its operation for at least one flight to enable the aircraft to land safely.

Those operational damages mentioned here have a sudden nature and lead to a dent or a fracture in the structure. Fatigue damage is also an operational damage, but with a gradual and high probabilistic nature. In general, fatigue damage starts from a location like a notch or a thickness step, where the stress concentration factor is increased. Fatigue exists of three phases, fatigue crack initiation, fatigue crack growth and final failure. A fuselage structure is designed such, that a fatigue crack is found during routine inspection. Therefore two criteria are important; the detectable size and the critical size of the crack. The instruments used during the routine inspections determine the detectable size of the crack; while the structural fracture toughness determines the critical size of the crack. The fatigue crack growth properties determine the amount of flights it takes to growth from the detectable crack length to the critical crack length and this determines the inspection intervals.

3.3 Inspectability

Different types of inspections are used to keep track of the health of the fuselage structure. Two main categories are: scheduled and unscheduled inspections. The unscheduled inspections are performed if during aircraft operation an anomalous situation occurred, like a hard landing or extreme turbulence during flight.

Different types of scheduled inspections exist, from a visual pre flight inspections at the platform to a D-check in which even the paint is removed to inspect the structure underneath it. The damage size that can be detected is dependent on the type of inspection. For instance, during a pre flight check only obvious damages can be detected which are in the line of sight. On the other hand, during a D-check, all the rivets are inspected for small fatigue cracks.

Because the location of the damage also determines whether it is found during inspection, different requirements exist for the critical damage size in the different location of the fuselage. For instance, a crack in the upper skin of the fuselage is not detected during a pre-flight inspection, while a damage around a cargo door probably is. Therefore the upper structure of the fuselage must be able to tolerate a larger crack than the lower structure of the fuselage.

3.4 Repair methods

The easiest and fastest repair method which is applied is the use of a riveted repair patch. Especially for damages with a sudden nature, a repair patch is applied at the airport where the aircraft is at the moment that the damage is detected. Because these damages are not limited to a certain location in the structure, it is possible that a damage occurs at a welded joint. Instead of a riveted or an adhesively bonded joint, an FS welded joint is not visible in the structure for the maintenance crew. Therefore, it is possible that a repair patch is placed with its rivets at the location in the FS weld with the lowest fatigue properties.

Other repair methods are available, up to the replacement of a damaged skin panel, but this is not preferable because the possibility to replace a skin panel is limited.

3.5 Damage tolerance design philosophies

In general, the approach used for the damage tolerance assessment of a fuselage structure is based upon the fatigue crack propagation properties of the structure. The crack propagation rate determines the amount of flights it takes to grow from a detectable crack length to a critical crack size. This amount of flights determines the inspection interval, because it is required that at least two inspections take place before a fracture can become critical. This approach is used to deal with damages of different origin and nature.

The fatigue initiation period does not play a role in this approach because it is considered that damage immediately leads to fatigue crack propagation. The fatigue crack initiation life is only important to determine the inspection threshold which influences the maintenance costs of new aircraft.

For a fatigue crack that is caused by operational stresses and not by damage, the same approach is used. The initial flaw criterion even states that a fatigue crack can start to propagate at the first moment the aircraft is used. Therefore most research is focused on the fatigue crack propagation properties and not on the fatigue crack initiation.

For the two-bay crack criterion a different approach is used, because the damage is immediately critical and thus no fatigue crack propagation phase is expected. For this case the fracture toughness of the structure is important and crack stoppers or frames are used to stop the fracture. In general, it is tried to make the fracture turn such that the crack tip is no longer perpendicular to the main stress. For such damages no scheduled inspection is required, because it is not possible to overlook such a large damage.

The two-bay crack criterion acts also as a safety net for all the other damages, for the case that they are not detected during the scheduled inspections.

4 Discussion

In this chapter two situations are distinguished: an FS weld without and with a rivet located in the weld. For the first situation, the mechanical and fatigue properties of the FS weld are discussed and what that means for the application in the fuselage structure. For the case with a rivet in the FS weld, it is discussed what that implies for the behavior of the fuselage structure.

4.1 Application of FS welds in the fuselage structure

The reduction of yield strength in an FS weld should be taken into account. Three solutions exist to deal with a lower yield strength. The first solution is to strengthen the structure by increasing the sheet thickness locally at the joint to reduce the stress. The second solution is to apply a heat treatment after welding in which the original mechanical properties are recovered. However, this is an expensive solution because in this case the whole part has to be heat treated, which requires a large oven and a high temperature control. The third solution is using a type of alloy with natural ageing capabilities. However, most high strength aluminum alloys are artificially aged because the naturally aged alloys have lower mechanical properties.

As was shown, FS welding introduces residual stresses with a high orientation dependency. In the design of a fuselage structure, those stresses should be taken into account by superposition on the operational stresses. This could imply that for a longitudinal joint, the longitudinal stresses can become critical instead of the circumferential stresses.

Because the fuselage structure is designed with a damage tolerance philosophy, the behavior of a damaged FS weld must be understood. The presence of a weld does not affect the size and the nature of the damage, but the properties of the weld influence the fatigue crack propagation rate. If the fatigue crack propagation properties for an FS weld are lower than for the undisturbed skin material, those properties must be used to determine the inspection interval.

Furthermore, some welds tend to attract the fatigue crack, and thus act as a highway underneath frames and crack stoppers. During fatigue experiments, some crack turning due to the presence of the FS weld was observed [11]. It is already proposed to use this behavior to prevent a fatigue crack for crossing a frame. The advantage of this behavior is that no additional crack stopper is required, which saves weight. However, this phenomenon is not yet understood well enough and requires additional research before it can be used safely.

For the two-bay crack criterion the fracture toughness of the weld must be high enough to prevent the fracture trespassing the frames to the surrounding bays. Besides, the FS weld must not prevent the fracture from turning up or downward away from an orientation perpendicular to the main stress. Again, it must be shown that an FS weld does not attract the fracture during static crack growth and does not lead it underneath the frames.

4.2 Design criteria for rivets near an FS weld

It is possible to design the structure such that rivets of frames and other structural elements are not placed in the FS weld. The area which should be kept rivet free is at least the size of the weld, including the heat affected zone. The size of the HAZ depends on the amount of heat input during welding and thus on the sheet thickness. In general, the size of the HAZ can be easily obtained by micro hardness tests.

During the operational phase of an aircraft, the location of damage cannot be controlled, and thus it is a plausible scenario that a repair is placed over an FS weld, with the rivets in the location with the worst properties. Therefore, the worst case scenario with the lowest possible properties for the mechanical and fatigue behavior must be considered for the evaluation of a repair patch.

4.3 Rivet flexibility

The efficiency of a rivet is depending on the rivet flexibility, which is highly influenced by the plastic deformation around the rivet hole [12]. The other properties which influence the rivet flexibility, i.e. modulus of elasticity,

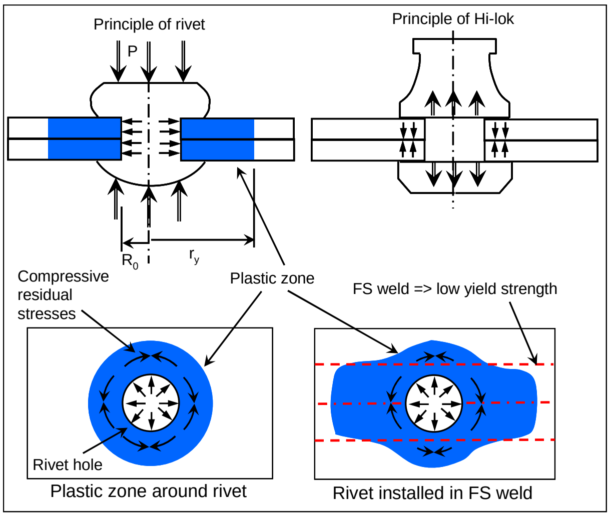

Fig. 8. Principle of plastic zone and residual stresses around a rivet

diameter and sheet thickness, are not changed by FS welding.

The plastic zone around the rivet is created by the squeezing force during the riveting process (Fig. 8). It is preferred to have a large plastic zone around the rivet because that will introduce residual compressive stresses as it is beneficial for the fatigue crack initiation life [12]. Those residual stresses can go up to 80 % of the yield strength. As described by equation 3 [12], the size of the plastic zone is related to the yield strength (σ_y), the squeeze force with which the rivet is installed (P), and the rivet diameter.

$$r_y = R_0 \cdot e^{\left(\frac{P}{\sigma_y} - \frac{1}{2}\right)} \tag{3}$$

As was described in section 2.1, the yield strength is reduced in an FS weld. The local lower yield strength influences the plastic zone size around the rivet and thus the compressive residual stresses. Because the FS weld is oriented in one direction, the yield strength can vary around the rivet hole which will vary the size of the plastic zone and thus the residual compressive stresses (Fig. 8). Therefore, the rivet flexibility is not equal in all directions and the fatigue initiation life of the rivet is affected differently for different direction of loading. It is expected that the fatigue initiation properties will be lowest for the L-T loaded case, because in that direction the lowest fatigue crack initiation properties are at the critical location of the hole. However, if the diameter of the rivet is smaller than the width of the area of reduced yield strength in the FS weld, no difference might be found between the T-L and the L-T case.

Beside the influence of the yield strength, also the residual stresses in the weld have a large influence on the fatigue crack initiation life [2,13-15]. The orientation of the residual stress field is parallel to the FS weld and high enough to overcome the residual compressive stresses created by the riveting process. Therefore, the largest reduction of the fatigue crack initiation life is due to the residual stresses is expected for the L-T case.

The results from the fatigue crack initiation test showed that the specimens loaded in L-T direction indeed gave the lowest fatigue crack initiation lifes. However, that research dealt with open hole specimen in which the influence of the rivet was not present. Besides, hole diameters of 1 mm were used which can not be related to rivet diameters. To enable the relation between the diameters, additional fatigue crack initiation tests were conducted with 4.8 mm holes in FS welds, to relate those results with the results of the specimens with 1 mm holes (Fig. 9).

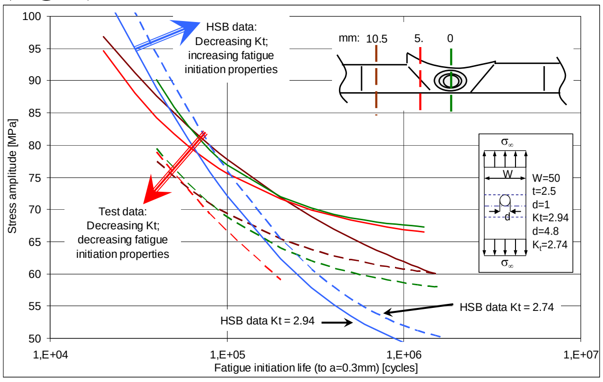

Fig. 9. S-N$_i$ curves of FS welded AA2024-T3 with two hole sizes: 1 mm and 4.8 mm, T-L direction, HSB data [16] is included for the tested K$_t$ factors.

Unfortunately, the 4.8 mm hole specimens were only tested in T-L direction, which later on appeared to be perpendicular to the direction with the highest differences.

Nevertheless, two observations can still be made relevant for the size-effect. First, the obtained fatigue crack initiation life of the 4.8 mm hole specimens was similar for the different locations in the FS weld. This seems to support the conclusion that perpendicular to the weld only small residual stresses are present.

Second, it was observed that the fatigue crack initiation lifes for the 4.8 mm hole specimens are lower than for the 1.0 mm hole specimens, despite the fact that the stress concentration factor (K_t) is lower. Taking the S-N curves from, for example, the Handbuch Struktur Berechnung (HSB) [16] for similar K_t values, these S-N curves show an opposite trend (Fig. 9). The difference in trend is related to the size-effect, which is not taken into account in the calculation of the K_t. This indicates that a designer should always be aware of the origin of data from such a handbook.

5 Conclusions

From the previous sections the following conclusions can be deduced:

- For evaluating a riveted repair in an FS weld, the lowest fatigue properties must be used. It is not possible to know a priori whether a rivet hole will be drilled in an FS weld or not.
- The radial expansion theory for rivets is invalid in a FS weld if the yield strength varies through the weld.
- Residual stresses parallel to the weld could make the longitudinal stresses critical.

Copyright Statement

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