Chapter 4
Microstructural Development due to FSW

4.1 Introduction
The microstructure of a friction stir weld is very characteristic and so a transverse section can be easily identified. The FSW process changes the microstructure and properties of the material. The amount of change is dependent on the position within the joint as well as many other variables such as alloy type, original microstructure and the process and weld parameters used to create the joint. The higher heat and more plastic deformation occurring towards the centre of the weld results in a different microstructural evolution than in the regions of lower heat and no deformation towards the weld extremities. The resulting microstructure is due to a combination of all the process and weld variables described earlier. When tools or processes are said to have been optimised, this means that the variables associated with the process have been tailored to provide the best microstructure possible for the required application of the weld. FSW is still an emerging technology, understanding the evolution of the microstructure is important for a wider acceptance of the technology.

4.2 Microstructural Evolution
The friction stir welding process can be used to intentionally change the structure of a material. FSW provides the structure with heat and deformation; both of which are beneficial for microstructural change. The asymmetry of the process coupled with both the rotation and linear movements of the tool make this a very complex evolution from parent material to refined equiaxed structures in the weld region. An FSW will differ in the transverse and longitudinal direction. To aid with the visualization of the weld structure the transverse section will be tackled first followed by the longitudinal section.

4.2.1 Weld Section - Perpendicular to Weld Direction
The cross-section of an FSW weld in an aluminium alloy is easy to distinguish. Certain features are present which indicate the tool and process used to carry out the joint. The simplest joint configuration is the butt joint and so this will be used for the examples of weld regions. These features are present in all the other joint configurations and are shown below in figure 4.1. To classify FSW welds, work has been completed at TWI to
characterize the different parts of a friction stir weld. These definitions will enable aspects of any kind of friction stir weld made in any kind of material to be easily identified and direct comparisons to be made. This is also to aid the implementation of ISO standards. Most of the research work use the terminology set out as guidelines by TWI [70-71].

Figure 4.1 Cross section of FSW butt weld, detailing the weld regions

A friction stir weld contains different regions. These different regions have different mechanical properties and microstructures depending on what level of heat and deformation was experienced. The weld region comprises of the area directly beneath the tool shoulder. In figure 4.1 the width of the weld region is approximately that of the tool diameter. The weld region is narrower at the bottom due to less influence from the tool shoulder and the tapering of the probe. However, his is not always the case, other variants of FSW processes and every different design of tool will create a differently shaped weld region but they contain the same features [70-71].

4.2.1.1 Weld Nugget

This section of the weld region, marked as (A) in figure 4.1, experiences high levels of heat and deformation. Aluminium is the only material studied which contains a separate nugget region. In other materials the nugget is part of the thermo-mechanically affected zone and is not a separate area [71]. The nugget region refers to the area which is passed through by the probe of the tool. Material is forced around the front of the tool probe before being extruded round the tool and filling in behind it. During the process the combined heat and deformation acting on the material tends to cause recrystallization. This recrystallization is dynamic in nature and is confined
to the weld nugget for aluminium and its alloys [18, 72]. For this reason the weld nugget is also referred to as the Dynamically Recrystallized Zone (DRX), the dynamic part referring to the mechanism of recrystallization occurring during the presence of deformation as well as heat [73]. There are many different terms being used to describe the various regions. Some of the names used for the weld nugget (WN) include, Stir zone, swirl zone and dynamically recrystallized zone [14, 71].

Recrystallization occurs as an evolution from the pre-welded base material structure. The evolution starts by introducing dislocations in the grains by plastic deformation. As the process goes on subgrains are formed by dynamic recovery. This is where the temperature causes the grains to move and become rearranged. This reduces residual stress in the grains [74-75]. The recrystallization and recovery steps continue until the driving force (residual stresses within the grain boundaries) diminishes, at this point grain growth takes over. The recrystallization process usually takes place as a discontinuous process with cycles of high heat and deformation, however it has been reported that the recrystallization occurring within FSW takes place continuously and is referred to as continuous dynamic recrystallization (CDRX) [76-78]. However, this theory is not accepted by everybody, with some considering the mechanism to be geometrical dynamic recrystallization (GDRX) [19]. CDRX is a continuous increase in subgrain boundary misorientation within the microstructure of the material. This is achieved by continuous heat and deformation as exhibited in the FSW process. This continuous misorientation is in turn attributed to dislocations being absorbed by the subgrain boundaries in order to accommodate plastic strains acting on the subgrains. This ultimately yields a fine grain structure containing fewer dislocations. Figure 4.2 shows dislocations being absorbed in the subgrain boundary.

![Figure 4.2 Dislocations, absorption by subgrain boundary during DRX](image)

Figure 4.2 Dislocations, absorption by subgrain boundary during DRX [79]

Figure 4.3 shows the difference between the base material structure and recrystallized
structure (a) and (b) respectively. The creation of the fine grain structure is based on a system of dynamic recovery and continuous dynamic recrystallization. Grains are heated and deformed which dislocates the grains, making them smaller and more uniform in size [75]. This uniform structure is very beneficial to FSP as mentioned in Section 2.7.4. The weld nugget’s structure is dramatically changed by applying localized heat and deformation to the material.

![Grain refinements after FSW via DRX](image)

Figure 4.3 Grain refinements after FSW via DRX (a) Pre-welded microstructure, (b) Fine grain structure after recrystallization [78]

4.2.1.2 Thermo Mechanically Affected Zone- TMAZ

This area marked as (B) in figure 4.1 is not subjected to the same amounts of heat or deformation experienced by the weld nugget material. As the name suggests however this area is both heated and deformed by the tool. Recrystallization in the weld nugget is homogeneous, recrystallization in the TMAZ in inhomogeneous. The same fundamental process exists within this area. The amount of heat and deformation is at its peak inside the weld nugget and then generally dissipates as the distance from this weld nugget increases. It is common for aluminium to exhibit both a weld nugget and a TMAZ which both contain recrystallization. However, it is possible for the TMAZ to not experience the dynamic recrystallization when deformation or temperature is insufficient [80]. Generally in aluminium there is only partial recrystallization in the TMAZ, mostly recovery. This applies to aluminium but not necessarily other materials where a separate weld nugget is seldom observed. This is due to the very high resistance of aluminium alloys to recrystallize [19]. The high stacking fault energy in aluminium means that the critical level of driving force for recrystallization is not reached in the TMAZ or is only reached sporadically meaning this part of the weld does not fully recrystallize.
4.2.1.3 Heat Affected Zone - HAZ

This is the last region of the weld cross section which experiences any change in structure or properties due to the FSW process. This area is located just outside the foot print of the tool and marked as (C) in figure 4.1. As the name suggests this area is heated by the presence of the tool as it traverses the joint. There is no macroscopic deformation occurring in this area and so it is affected by possible aging and or over aging [12, 71]. Without induced deformation the structure of the HAZ is either strengthened or weakened by the heat from the process, this depends on the temper of the aluminium being welded. Recovery acts upon this region, the grains remain larger in size compared to the previous zones described above because there is no deformation to recrystallize the structure.

The HAZ can be compromised due to an over-aging effect of the tool. If a fully aged alloy was subsequently friction stir welded the tool would overage and weaken the HAZ region, however if an O (annealed) temper material is used the tool may age and therefore strengthen the HAZ [19]. Aging, especially artificial aging is applied to evolve the physical properties of a material [12]. The material is heated to a precise temperature for a precise amount of time to maximize mechanical properties like strength and hardness. The time and temperature of this is critical. Too higher temperature or too long a time or both will result in over aging and weakening of the material. This means that the amount by which the HAZ is weakened depends on the inputs to the process, tool rotation and travel speed. A slow tool rotation and fast travel speed (high welding pitch) would yield a far smaller and shorter period at elevated temperature. Consider a fast tool rotation and slow travel speed (low welding pitch), this would result in a far larger temperature and longer time at this high temperature and so would be more influential to the properties of the HAZ [12]. The general weakness of this region, in fully heat treated materials, is associated with larger grains and is easily characterized by a hardness profile plot containing hardness minima at the point corresponding to the HAZ region. Figure 4.4 shows such a hardness plot for a precipitation hardening alloy. The distinct W shape shows the weakness associated with the HAZ region. Towards the centre of the weld the material is deformed allowing recrystallization to occur. The further from the weld centre the less deformation influences the material until the edge of the tool shoulder is met and deformation stops. When the material is heated without the presence of
deformation it causes weakening of the material due to coarsening or even dissolution of the strengthening precipitates [71] giving rise to the minima seen in figure 4.4.

Figure 4.4 Common hardness profile of a cross section of a weld in AA2024-T351 [81]

4.2.1.4 Parent Material

This area, marked as (D) in Figure 4.1, is unchanged throughout the entire process. The heat emanating from the tool does not affect this region. The HAZ is not under the tool footprint and so it is a transitional region between the unchanged parent material, the highly deformed TMAZ and weld nugget. Generally the physical properties of the parent material are superior to those of the welded zone; however it has been known for welds to fail in this unaffected zone rather than the weld itself.

Figure 4.5 Macrographs of weld regions (a) Parent Material, (b) HAZ, (c) TMAZ, (d) Weld Nugget Extremity, (e) Weld Nugget Centre [29]

Figure 4.5 shows the transition of a cast aluminium parent material structure through the different weld regions from the cast structure in (a) to the fine equiaxed structure
within the weld nugget in (e). This represents the extremes of the structural change at work during FSW. The first considerations are the fine structures in pictures (d) and (e). This is the weld region and so exhibits fine equiaxed grains. These grains are larger in (c) which shows the difference in recrystallization between the two regions. Larger grains still are found in the HAZ, picture (b), along with some of the dendrite parent material structure. The completely unaffected material shown in a) contains only the casting solidification structure.

4.2.2 Weld Section - Parallel to Weld Direction

FSW creates a very distinguishable transverse cross section as detailed above, however it also creates a highly characteristic longitudinal cross section. When an FSW is observed the track left by the tool is instantly noticeable. This track also known as scalloping and consists of individual bands of swept material. In Chapter 2 section 2.4.1, the material flow is described; material is swept by the tool from advancing side to retreating side, this action results in the banded structure shown in figure 4.6.

![Figure 4.6 Banded Structure of FSW in a Longitudinal Cross Section [81]](image)

This banded structure exhibits two distinct alternating structures. These bands are shown in greater detail in figure 4.7. The microstructure and hence grain sizes are different for the two bands. Sometimes the grain size separates the two bands; band A can show finer grains when compared to band B. The causes of the banded structure are not fully understood, but are not considered important as there are no detrimental effects caused by them [19]. It is however hypothesized that this
structure is due to the distribution of second phase particles within the weld. Studies show that band A contains a higher density of second phase particles [81].

![Banded Structure Grain Variance](image)

**Figure 4.7 Banded Structure Grain Variance [81]**

These particles affect the hardness of the material, the more particles the harder the material, and this is clarified by figure 4.8. It is also hypothesized by Yang et al that the difference in precipitation density in the banded structure could affect the microstructure at high temperatures; resulting in the bands experiencing recrystallization, recovery and abnormal grain growth at different intervals.

![Knoop micro-hardness (KHN) Vs distance in weld direction for bands A-B](image)

**Figure 4.8 Knoop micro-hardness (KHN) Vs distance in weld direction for bands A-B [81]**

In studies of these bands it has been noted that the spacing of the bands is equal to the distance travelled along the weld direction by the tool in the time taken to complete one tool revolution [28, 81].
4.2.3 Precipitation Distribution and Coarse Grain Dispersal

Coarse precipitates within the structure are broken down and refined by FSW but are still far larger than the fine grains created in the weld region by the CDRX process. These second phase particles or precipitates affect the properties. It is reported that more, smaller particles are found on the advancing side of friction stir welds with the retreating side containing larger particles [81]. These particles and their arrangements are believed to affect the properties. The most common failure site for a FSW butt weld is on the retreating side of the weld. This suggests that larger particles are detrimental to the weld properties [81].

4.2.4 Variation of FSW Microstructure with Process and Weld Variables

The final microstructure of an FSW is reliant on the process variables and tooling geometry used to create the weld. For a given tool, variations to the primary process variables; spindle speed and welding speed (feed speed), have the most influence over the microstructural evolution of a friction stir weld [70]. However the tool itself has the greatest say on the final weld structure created by determining the size and shape of the weld region, the amount of heat and deformation experienced and the size and position of any weld defects.

It has been established that fast welding speeds coupled with slow spindle rotations give rise to low heat inputs during welding [31]. Low levels of heat input for FSWs allows for significant reduction in grain size via the dynamic recrystallization mechanisms in the weld nugget [25, 26, 27, 82] and more favourable microstructures for subsequent forming operations. Generally the lower the FSW heat input, the finer the grain size and so more strength is retained post welding; this occurs due to a reduction of static annealing processes induced by the tooling as it processes the weld material; minimizing the amount of recovery and therefore grain coarsening within the weld region [83].

Taking the spindle rotation first; the faster the spindle is rotated the more frictional heat is generated beneath the tool, increasing the extent of the influence of the heat field generated by the FSW tooling. This means that increasing the spindle speed will increase the final grain size of the weld material [83]. This can occur due to the FSW process offering the weld material sufficient energy for microstructural change for recovery or secondary recrystallization allowing the grains to grow within the weld region. The increased spindle speed and therefore increased heat input can also
destabilize the microstructure due to coarsening or dissolution of important second phase strengthening particles which pin the grain boundaries. If the size and distribution of these second phases are significantly affected the weld region may be prone to abnormal grain growth. Figure 4.9(a) shows grain size versus FSW spindle rotation speed for AA2524-T351 [83]. For a constant feed speed, as the rotation speed increases the grain size also increases. At first there is a sharp increase in grain size before it levels off to a plateau in a similar way the FSW heat input; where above a certain point no more increase in heat is possible for an increase in spindle rotation; due to the self-regulating frictional heating mechanism which stops fusion temperatures from being reached. Figure 4.9(b) shows the variation of grain size versus with welding speed. The trend here shows that the faster the welding speed the greater the grain refinement and therefore the smaller the final grain size [83].

![Figure 4.9 Effects of rotational and welding speed on nugget grain size](image)

Manipulating the grain size data from Yan et al [83] to give the grain size versus welding pitch gives the graph shown in figure 4.10. The welding pitch is a useful value for estimating the heat input for a friction stir weld; a high welding pitch represents a cold welding parameter set with a large amount of material processed for each revolution of the tooling, compared to a low welding pitch where a small amount of material is process for each tool revolution. It is clearly visible that as the welding pitch increases (heat input decreases) the grain size of the material in the weld nugget decreases for both a constant rotation speed and a constant welding speed. This grain refinement, for a reduction in FSW heat input, is mirrored in AA7010 [84], AA2024 [85] and AA5083 [86]. Reducing the heat input applied during welding reduces the grain size of the weld material; a fine grain size is more favourable for subsequent high temperature forming.
Looking briefly at material from outside of the weld region, the FSW heat input plays a part in the size and strength of the Heat Affected Zone. As the FSW heat input decreases (either by decreasing the rotation speed or increasing the welding speed) the hardness of the HAZ increases due to the reduced annealing effects of the tooling. The heat field generated by the tool as it passes over the material is reduced in magnitude and has a reduced affect on the weld material [83]. The final grain size of the FSW microstructure can be further refined using quenching techniques and or low temperature welding techniques. Benavides et al [87] have produced grain sizes in the nano range using a liquid nitrogen cooled FSW system. Removing the vast majority of the heat from the process; ultra fine grains are produced, the liquid nitrogen also acts as an instant quench, locking in the refined microstructure and maintaining its size even after the tooling has left the vicinity of the material.

4.2.4.1 Variation of Structure with Tool Geometry

Many studies have been carried out in order to establish the best tooling for friction stir welding [1, 7, 11, 12, 14, 33, 88]. It is now recognized that tooling with external probe features produce the best welds and most favourable microstructures. This is due to the influence of the tool probe during FSW. It is the job of the tool probe to deliver heat and deformation to the weld root; allowing total annihilation of the joint interface. Smooth, featureless tooling does not exert enough influence towards the weld root and so the joint interface remains and acts as a failure initiation site and ultimately a flawed weld. The inclusion of re-entrant features such as threads, flats and flutes increases the size of the weld nugget and so also the
deformation throughout the through thickness of the weld material; ensuring bonding right to the very bottom of the weld. They also play a part in refining the grain structure and reducing FSW heat input by reducing the static volume while maintaining the dynamic rotating volume [33].

For a given process variable set; the choice of tooling makes a difference in the weld structures produced. Smooth tooling will produce larger grains than re-entrant tooling due to a decrease in interaction between the tooling and the weld material [89]. Smooth tooling will slide over the weld material and reduce the amount of deformation; whereas re-entrant tooling will entrap weld material and distribute it within the weld region and so will cause more deformation and more grain refinement [33]. The tooling geometry may also influence the size and position of any weld defects such as worm holes, kissing bonds and voids. This is mostly associated with smooth tooling as they exert less deformation on the weld material and may leave unprocessed material within the weld region. A tool with threads and either flutes or flats is considered to be the best for friction stir welding of aluminium [30]

4.2.5 Friction Stir Welding in 6xxx Series Aluminium Alloys

Concerning the FSW of the 6xxx series of aluminium alloys, the 6061 series was studied, either in similar [90-97] and dissimilar [98-103] welding combinations. Also the effort was spent in studying the FSW of the 6082 [104-115], 6063 [116-118], 6056 [119-120], 6022 [121], 6005 [122], 6013 [123], 6016 [124], 6016[125], 6351[126], and 6056[127] series of alloys. Some of the materials used for hot extruded automotive parts are light and strong aluminium alloys from 6xxx group. The main requirements for the alloy are sufficient plasticity for extrusion, high friction resistance in the slide pair with steel parts, ample strength and resistance to the dynamic strains. Al-Mg-Si alloy 6082 is the best choice for this purpose. Alloy 6082 (EN AW-6082) is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6xxx group alloys. Also, alloy 6082 offers good weldability, brazeability, formability and machinability. It contains only 2-3% alloying additives, thus its strength is lower comparing with duralumin, but plasticity and corrosion resistance are excellent. The principal alloying elements in AA6082 are Si, Mg and Mn that play important role on structure and properties of the alloy. In most of these studies the thicknesses of the plates joined ranged from 3 to 6 mm. FSW results in generation of various microstructural zones- the nugget zone, the TMAZ, and the HAZ.
These zones exhibit different microstructural characteristics such as grain size and dislocation density, residual stress and texture, and precipitate size and distribution. Therefore, it is expected that the various microstructural zones will exhibit different corrosion behaviour. For practical applications, it is very important to understand corrosion behaviour of the FSW welds and elucidate the prevailing mechanisms for corrosion in various FSW alloys and various microstructural zones. In the past few years several studies were conducted with the aim to understand the effect of FSW on the corrosion and stress corrosion cracking [128-152].

4.4 Summary

A brief explanation of some key microstructural terminology is offered before explaining the resulting weld regions. The friction stir welding process characteristic weld regions are depicted and explained. These regions undergo very different thermal and deformation cycles and so produce very different microstructures. These different structures are described along with how the starting structure has evolved into its final form.