ANALYSING THE EFFECT OF FRICTION STIR PROCESSING ON MIG-LASER HYBRID WELDED AA 6082-T6 JOINTS

KADEPHI VUYOLWETHU MJALI
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Analysing the effect of FSP on MIG-laser hybrid welded 6082-T6 AA joints

By

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Submitted on.....................

Signed.............................
AUTHOR’S DECLARATION

I, Kadephi Vuyolwethu Mjali hereby declare that:

▪ The work done in this thesis is my own

▪ All sources used or referred to have been documented and recognised and,

▪ This thesis has not been previously submitted in full or partial fulfilment of requirements for an equivalent or higher qualification at any other educational institution
ACKNOWLEDGEMENTS

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Friction Stir Processing (FSP) of aluminium alloys has been used to modify and improve the microstructure and relevant properties of fusion welded aluminium alloys. The effect of FSP on MIG-Laser Hybrid (MLH) welded aluminium alloy 6082-T6 mechanical and microstructural properties has been studied in this research. The FSP process was used on 6mm thick aluminium alloy plates and a tool was designed specifically for FSP, and the effect of varying speeds was analysed before the final FSP welds were made.

The effect of FSP was analysed by optical microscopy, tensile, microhardness and fatigue testing. The aim of the study was to determine whether the FSP process has a beneficial influence on the mechanical properties and metallurgical integrity of MIG-Laser Hybrid welded 6082-T6 aluminium alloy with varying gap tolerances. Three welding processes were compared, namely combined Friction Stir Processing on MIG-Laser hybrid process (FSP-MLH), MLH and Friction Stir Welding (FSW) as part of the analysis. (FSP was carried out on MLH components when it was found that FSP is not an entirely complete welding process but rather a finishing process per se.) The aim of this dissertation is to investigate the effects of the FSP process on the weld quality of MLH welded joints and also to compare this to individual processes like FSW and MLH. This investigation was undertaken in order to gain an understanding of the effect of these processes on
fatigue performance and microhardness distribution on aluminium alloy 6082-T6 weld joints.
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<td>MIG</td>
<td>Metal Inert Gas</td>
</tr>
<tr>
<td>TWI</td>
<td>The Welding Institute</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction Stir Welding</td>
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<tr>
<td>AA</td>
<td>Aluminium Alloy</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ALC</td>
<td>African Laser Centre</td>
</tr>
<tr>
<td>MTRC</td>
<td>Manufacturing Technology Research Centre</td>
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<tr>
<td>MLH</td>
<td>MIG-Laser Hybrid</td>
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<tr>
<td>TIG</td>
<td>Tungsten Inert Gas</td>
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<td>FSP</td>
<td>Friction Stir Processing</td>
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<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
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<tr>
<td>TMAZ</td>
<td>Thermo Mechanically Affected Zone</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
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<tr>
<td>GP</td>
<td>Guinier Preston</td>
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<td>PALW</td>
<td>Plasma Arc augmented Laser Welding technology</td>
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GLOSSARY OF TERMS

A

Alloying element: An element added to the metal and causes a change in structure and properties.

Annealing: Consists of heating the material and then cooling it very slowly and uniformly; the time and temperatures required in the process are set according to the properties desired.

As manufactured: Refers to sheet metal in its manufactured form.

Abrasive paper: These are special papers coated in grit, which are used for flattening down and are supplied in a wide range of grits from very fine to coarse material. They can be specified to be either dry or waterproof.

Advancing side: Side of the weld where direction of travel is the same as the direction of rotation of the shoulder.

Anvil backing bar: The supporting member used to react to the forces applied to the workpiece to minimize material distortion. A secondary function is to prevent plasticized material extruding from the underside of the joint.

B
**Butt weld:** A butt joint that has been joined by welding.

**C**

**Capillary action:** This phenomenon is associated with surface tension and resulting in the elevation or depression of liquids in capillaries.

**D**

**Deformation:** This is an alteration of shape, caused by pressure or stress.

**Dwell time:** The period of time after the rotating tool has been plunged into the work and for which it remains stationary, generating frictional heat and plasticizing the material, before commencing the traverse along the join (secs).

**Down or axial force:** The required force applied to the FSW tool, to plunge the probe into the work piece and maintain shoulder contact with the surface on the work piece (kN).

**E**

**Etchant:** This a chemical solution used to reveal micro structural details of a metal.

**Etching:** This is subjecting the surface of a metal to a preferential chemical or electrolytic attack in order to reveal structural details for metallographic examination.
Exit hole: A hole left at the end of the weld when the tool is withdrawn, resulting from the displacement of material during the tool plunge or pilot hole drilling operations. Some special techniques are in use to fill or prevent the occurrence of this hole.

Fatigue: Used mostly in engineering, microscopic cracking of materials, especially metals, after repeated applications of stress.

Fusion welding: Involves a heat source and may involve the use of a filler material such as a consumable electrode or a wire fed into the weld pool.

Fatigue life: The number of load cycles a component can withstand before failure.

FEA (Finite Element Analysis): A mathematical technique, for analyzing stress, which breaks down a physical structure into substructures called "finite elements". FEA is the analysis of static and dynamical systems using computational methods such as the finite difference method.

Grain growth: The enlarging or coarsening of the individual grains within the metal or alloy during heating at a temperature above the recrystalization temperature.
**H**

**Hardness:** Property of matter commonly described as the resistance of a substance to being scratched by another substance. The degree of hardness is relative, different substances being compared with one another and the term describes material resistance (resistant) to plastic deformation under the action of an indenter.

**Heat Affected Zone (HAZ):** When welding aluminium alloys the heat produced by the arc will lower the mechanical properties in and near the weld and the zone near the weld with lowered mechanical properties is called the heat affected zones (HAZ).

**Hardening:** Treatment of metals to increase their resistance to penetration.

**Homogenous:** Having the same chemical composition and physical state throughout the material.

**Hot hardness:** Indicates the metal's resistance to the softening effect at elevated temperatures.

**Heel plunge depth:** Distance by which deepest part of tool shoulder penetrates below work piece surface.

**L**
Lap joint: A joint, as between two boards or metal parts, in which the ends or edges are overlapped and fastened together, usually so as to produce a flush or continuous surface.

Mechanical properties: The properties of a material that reveal its elastic and inelastic behaviour when force is applied, thereby indicating its suitability for mechanical applications.

Microstructure: The structure of an organism or object as revealed through microscopic examination.

Macrostructure: The structure of metals as revealed by macroscopic examination of the etched surface.

Non-fusion: The process where the materials are not liquefied or melted to form a bond, however with heat applied to reduce the energy required to cause plastic deformation.

Onion-skin flow pattern: The characteristic weld pattern featuring a cyclic ring or onion skin-like profile.

Oxidation: The addition of oxygen to a compound and, more generally, any reaction that involves the loss of electrons.
Principal strain: The maximum and minimum direct strains in a material, subjected to complex stress, are called principal strains, and act in the direction of the principal stress.

Principal stress: At any point within a stressed material it will be found that there exist three mutually perpendicular planes on each of which the resultant stress is a normal stress (no shear stresses occur on these plains). These mutually perpendicular planes are called principal planes and the resultant normal stresses are called Principal stresses.

Plastic deformation: The permanent distortion of materials under applied stresses that strain the material beyond its elastic limit.

Parent Material: The original material that has not been affected, by heat or pressure.

Polishing: Smoothing metal surfaces, often to a high lustre, by rubbing the surface with a fine abrasive, usually contained in a cloth or other soft lap.

Pilot hole: In some cases it is advisable to pre-drill a hole in the workpiece, into which the FSW tool can be plunged. This is particularly relevant when welding hard or thick section materials.
**Plunge force:** During the plunging stage of the tool pin in FSW, the vertical force in the direction of the Z-axis movement is normally referred to as the plunging force.

**Q**

**Quenching:** The rapid cooling of a solid to lock it into a metastable crystal structure rather than to allow it to cool slowly and revert to a softer structure. It is most commonly used to harden steel by introducing martensite, in which case the steel must be cooled from a temperature at which austenite is stable.

**Quench hardening:** In ferrous alloys, hardening by austenitising, then cooling down at a rate so that substantial amount of austenite transforms to martensite.

**R**

**Recrystallization:** Is the growth of particular grain fragments in a metal or alloy at the expense of others. This occurs when the metal or alloy is severely worked, as by cold rolling. Recrystallization results in greater, strain-free grains.

**Residual stress:** The residual stresses in a component or structure are stresses caused by incompatible internal permanent strains. They may be generated or modified at every stage in the component life cycle, from original material production to final disposal.
**Restrained**: The act of holding back any movement in any direction.

**Rolling direction**: Refers to the direction in which the billet was rolled during the sheet metal plate manufacture.

**Retreating side**: Side of the weld where direction of travel is opposed to direction of rotation of shoulder.

**Spindle speed**: The peripheral speed of a work piece passing the cutter in a CNC turning centre or cutter passing the work piece in a CNC milling machine.

**Stress**: Internal force exerted by either of two adjacent parts of a body upon the other across an imagined plane of separation. When the forces are applied parallel to the plane, the stress is called shear stress; when the forces are normal to the plane, the stress is called normal stress; when the normal stress is directed toward the part on which it acts, it is called compressive stress; and when it is directed away from the part on which it acts, it is called tensile stress.

**Strain**: The measure of deformation of a body acted upon by external forces and can be expressed as a change in dimension per unit of original dimension.
SEM (Scanning Electron Microscopy): This is an electron microscope, which emits a very fine beam of electrons at (5 -100) kV and is made to scan a chosen area of specimen as a raster of parallel contiguous lines.

S-N curve: This is a plot of stress versus the number of cycles to failure the stress evaluated can be the alternating stress amplitude or the maximum stress.

Strain gauge: This is a strain-measuring instrument made from a metal or semiconductor filament on a backing sheet by which it can be attached to a body subjected to strain. The strain will alter the electrical properties of the filament, which is the basis of measurement.

Solid-state welding: A joining process in which coalescence results from application of pressure alone or a combination of heat and pressure whereby the temperature of the process is below the melting point of the metals being welded.

Spindle torque: The spindle torque required to rotate the FSW tool when plunging into and traversing through the work piece along the joint (Nm).

Sideways tile angle: Angle by which the tool is inclined away from the vertical, in a direction traverse to the welding direction.
**T**

**Thermo-Mechanically Affected Zone (TMAZ):** The metal has been plasticized and mechanically "stirred," but not heated enough to cause significant changes to metallurgical properties.

**Tempering:** Process involving slow and moderate heating to increase the hardness and toughness of metals that have undergone previous heat treatment. Metals are usually hardened by being heated to high temperatures and quenched rapidly. This treatment causes brittleness, which is reduced by tempering. Steel is notably responsive to tempering, and makers of tools, weapons, armour, and other articles of steel have long had great skill in the process.

**Tensile strength:** The tensile strength of a material is the maximum amount of tensile stress that it can be subjected to.

**Thixotropic:** The property exhibited by certain gels of becoming fluid when stirred or shaken and returning to the semisolid state upon standing.

**Tool shoulder:** That part of the tool that rotates in contact with the surface of the workpiece.

**Tool pin (or probe):** That part of the tool which penetrates the workpiece surface.
**Tool rotation speed:** The rotation speed of the tool. This can be quoted as rotation speed (rev/min), peripheral velocity (m/s), or angular velocity (rad/sec).

**Tool tilt angle:** The angle at which the FSW tool is positioned relative to the work piece surface, i.e. zero tilt tools are positioned perpendicular to the workpiece surface (degrees).

**Tool plunge:** The process of forcing the tool into the material at the start of the weld. Plunge rate is measured in mm/sec.

**Tool shoulder footprint:** Area of shoulder in contact with workpiece surface.

**Transverse force:** The force required to translate the rotating FSW tool through the work piece material along the joint (kN).

**Traverse speed:** The speed at which the rotating FSW tool is translated along the joint line (mm/min).

**Unaffected material:** The bulk of the material which is not affected by either heat or deformation during welding.

**Viscosity:** The resistance of a fluid to flow. This resistance acts against the motion of any solid object through the fluid and also against motion
of the fluid itself past stationary obstacles. Viscosity also acts internally on the fluid between slower and faster moving adjacent layers.

**Void:** A noticeably empty space, such as a defect like a bubble in a (generally solid) material. The space that exists between particles or grains is called a void. In welding voids are related to surface defects.

**W**

**Wear resistance:** the gradual erosion of the tool’s operating surface, most conspicuously occurring at the exposed edges.

**Weld root:** The part of the joint profile opposite the shoulder is designated the root of the weld. Flaws can be evident in this area if welding conditions are incorrect.

**Workpiece/material:** The substrate or component to be welded.

**Weld nugget or stirred zone:** The recrystallised central area of the Thermo-Mechanically Affected Zone (TMAZ)

**X**

**X-axis:** Relating to a specific axis (horizontal) or affixed line determining the direction of movement or placement in a 2D or 3D coordinate system.
**Y**

**Y-axis:** Relating to a specific axis (perpendicular to x-axis) or a fixed line determining the direction of movement or placement in a 2D or 3D coordinate system.

**Z**

**Z-axis:** Relating to a specific axis (vertical) or a fixed line determining the direction of movement or placement in a 2D or 3D coordinate system.
1.1. INTRODUCTION

Increasing global competition in the assembly of automotive components as well as cost saving measures has forced automotive manufacturing companies to find alternative means, for the assembly process, that are cheaper, faster and not as labour intensive. These processes are more likely to have an influence on the design, engineering and manufacturing of passenger vehicles in future. A lot of emphasis has been placed on the manufacture of fuel-efficient vehicles, increased use of lightweight materials as well as more efficient and cost-effective processing techniques. Friction Stir and MIG-laser hybrid welding processes are at the forefront of the new technological developments.

The Friction Stir Welding (FSW) process is a relatively new welding technique used in the joining of aluminium alloys invented in the United Kingdom by TWI (The Welding Institute, Cambridge, UK) in 1991. The primary physical principle of this method is using a specially designed rotating pin tool to plunge into the interface of the work pieces. The main parameters of the FSW process are welding speed, spindle rotational speed, the clamping mechanism, the tool displacement forces, the dwell time and the angle of tool inclination.
If all the mentioned parameters are properly controlled, a good weld is guaranteed. Compared to other fusion joining processes the FSW process produces no porosity and there is good repeatability of the process. No special preparation is normally required of the plates to be welded and no filler material is required compared to competing fusion welding processes. Figure 1.1 shows the setup of the Friction Stir Welding process with the tool and the plates to be welded. The terms applicable to the FSW process are explained in the figure.

Another technique that promises good results is the MIG-laser hybrid welding process, which couples laser beam welding with a conventional welding process such as MIG-welding process. The first attempts to join a laser and a conventional welding torch into one welding process were performed in the late seventies at Imperial College, London, by a group lead by William Steen [Steen et al 1978].
Their tests showed clear advantages of combining a plasma arc to a $CO_2$ laser process, with increases in welding speed of $50\%-100\%$ and of $20\%$ increase in penetration depth as compared to pure laser welding. However encouraging these results did not immediately spur extensive activities in the area of laser hybrid welding. The MIG-laser hybrid welding process causes roots, the size of which varies due to the gap between the two welded plates and a variety of other factors [Steen et al, 1978]. Figure 1.2 shows the setup of the MIG-Laser Hybrid process with all the parameters involved.

![Figure 1.2 : MIG-Laser Hybrid process setup (Peggy Manara, Institute de Soudure, France)](image-url)
The hybrid process was developed to combine advantages of both laser welding and conventional MIG/TIG welding while trying to limit the shortcomings. Speeds are high and tolerances are better than for laser welding. The main parameters include laser power, welding speed (same as laser welding), focusing, filler wire and its speed, the distance between the laser spot and the filler wire or the electrode, welding sense (laser in front of the filler wire or behind it), intensity and voltage, and the shielding gas. For the preparation of the joint it depends on the plate thickness and for thicknesses less than 4 mm, butt welds can be done without machining of the plates but for thick sheet, chamfers (in the form of "V" or "Y) are done if one wants to weld in one pass [Manara et al, 2006].

Friction Stir Processing (FSP) is an emerging metal working technology that can provide localized modification and control microstructures in near surface layers of processed metallic components [Mishra et al, 2003]. The technology represents an adaptation of the principles of friction stir welding, a solid state joining process originally developed at The Welding Institute [Thomas et al, 1995]. Friction stir processing (root dressing) can be considered a bi-alloy process (parent and filler alloys), where the tool pin design and plate orientation (advancing and retreating side of tool) are important for proper bi-alloy mixing. Friction stir processing produces thermo mechanical deformation for local property enhancement of cast and wrought alloys [Mishra et al, 2000].
The benefits of FSP include elimination of porosity and microstructural refinement. The MIG-laser hybrid (MLH) welded specimens obtained for this research project had roots formed as a result of the MLH process that had to be root dressed (friction stir processed) to improve the surface finish and mechanical properties. The process used to do that is known as Friction Stir Processing and it is an adaptation of the FSW process with major differences being in the tool designs used and minor adjustments to the process but the principles are the same.

1.2. OBJECTIVE

The objective of the research was to investigate the effects FSP process has on the weld quality of MIG-laser hybrid welded joints of 6082-T6 with varying gap tolerances (0mm, 0.5 mm, 1.0 mm), in relation to mechanical properties. The following subproblems were identified to effectively analyse the process.

Subproblem 1

- Does the FSW root dress [FSP] process have an influence on tensile and hardness distribution of MIG-laser hybrid welded 6082-T6 aluminium alloy joints?

Subproblem 2

- Does the FSW root dress [FSP] process have an effect on fatigue life of MIG-laser hybrid welded 6082-T6-aluminium alloy joints?
Subproblem 3

- Does the FSW root dress [FSP] process have an influence on the metallurgical integrity of MIG-Laser Hybrid welded specimens?

1.3. DELIMITATIONS

- FSP was performed on MIG-laser hybrid welded specimens of 6082-T6 with a thickness of 6 mm.
- The FSW root dress [FSP] process was limited to one chosen tool type for consistency.
- Machine settings viz: feed rate, spindle speed, tilt angle were kept constant.
- Fatigue testing at single load was performed on the 6082-T6 plates.
- The depth of penetration for FSP was limited to 3mm.

1.4. ASSUMPTIONS

The research is based on the assumption that the 6082-T6 welded plates received from the African Laser Centre (ALC) were of good quality. The FSP process done on the plates will improve joint strength and cause an improvement in the fatigue life of the 6082-T6 MIG-laser hybrid welded joints. The tool was designed for the sole purpose of FSP and not FSW even though it had the capability of being used for FSW.
1.5. **HYPOTHESIS**

The FSP process will enhance the mechanical properties of MIG-Laser Hybrid welded 6082-T6 aluminium alloy. The mechanical properties will be improved because of the improvement/refinement of the grain structure due to FSP.

1.6. **OBJECTIVES OF THE RESEARCH**

- To enhance the existing knowledge of FSW and the MIG-laser hybrid-welding processes of 6082-T6 as used in the automotive and shipbuilding industries.
- To determine the gap with the best mechanical properties.
- To determine if the Friction Stir Processing [FSP] process has an influence on fatigue life, hardness and tensile properties of MIG-Laser hybrid 6082-T6.

1.7. **SIGNIFICANCE OF THE RESEARCH**

The research is very important to the international Friction Stir Welding community as it will add more data to the applications of the FSW process. At the moment no guide has been developed for Friction Stir Processing characteristics and design applications; therefore the manufacturing industry stands to benefit from this research as new joining techniques, which do not greatly affect fatigue strength, are always desired. It was envisaged that the FSP process would enhance fatigue performance in MIG-laser hybrid welded aluminium alloy
components and information from this research will help the manufacturing industry in understanding the benefits of Friction Stir Processing on MIG-Laser hybrid welded specimens, taking gaps into consideration. The outcomes from this research will add more parameters to FSW applications and also act as a guide to future researchers of the Friction Stir Processing process. This research will open up new possibilities about the combination of FSW-MIG-Laser hybrid welding processes and gap influence on Friction Stir Processed MIG-Laser Hybrid welded aluminium alloy plates will be determined. The research would further enhance the institution’s reputation as being one of the institutions in the world at the forefront of research and development in Friction Stir Welding and Laser materials processing.

1.8. RESEARCH METHODOLOGY

Before starting with the research, parameters that have an influence on the weld quality had to be established as well as determining the best setup in terms of spindle speed, pin force, tool design and feed rate. Once these had been well defined and understood, FSP was carried out on the specimens provided. The samples were root dressed at the MIG-Laser hybrid welded joints using the Friction Stir Welding machine and all samples were monitored.

The concept tool shown in Figure 2.33 was used for root dressing but the depth of penetration limited to 3mm. The clamping mechanism was also looked at and a complete redesign done. Aluminium alloy 6082-T6
with the same joint gaps (0, 0.5 mm and 1.0 mm) was welded on the FSW machine for comparative purposes. This assisted in the analysis of results as findings from testing Friction Stir Welded parent material gave an indication of the differences in mechanical/metallurgical properties of MIG-laser hybrid welded joints.

Tensile samples were prepared for mechanical testing according to ASTM standards [E466-96 and E8]. Fatigue, hardness and tensile tests were carried out for each set of parameters and results recorded during and after the testing procedure. Scanning electron microscopy together with optical microscopy was used to determine the relationship between joint microstructure and parent material. The fatigue life of MIG-Laser hybrid welded joints was compared to that of Friction Stir Processed and Friction Stir Welded joints.

According to published literature, the FSW process has the best fatigue strength when compared to existing fusion joining processes. FSW welded plates were used in the analysis and the selection of the stress levels used in fatigue testing. Since it was envisaged the FSW will have the best mechanical properties, FSW specimens formed the basis for comparison of the three processes.

A layout of the research conducted is shown in the diagram in Figure 1.3.
Figure 1.3: Flow diagram of research conducted
1.9. SUMMARY

The dissertation gives some background and insight into fusion welding and friction-based welding processes. The research will contribute to knowledge available on friction-based processes and also how these processes could be utilised to improve fusion-based welding processes to improve weld performance. The FSP tool designed will form the basis for future FSP designs for the friction stir processing of other aluminium alloys. The following chapter explains in detail all the processes mentioned briefly in this chapter.
CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

In machine design or any design field, materials are chosen for their suitability under specified design conditions, and cost factors are taken into consideration. Lifetime performance and mass become the deciding factors in choosing the material to be used. At the moment the automotive industry is trying to get the best out of available materials in order to improve and reduce fuel consumption and maintenance costs. Aluminium is the material of choice in the automotive, marine and aviation industries due to its versatility and it is the second mostly used material after steel due to its low weight and high strength. It can be joined easily by welding, brazing, soldering, mechanical fastening and adhesive bonding.

The MIG-Laser Hybrid and laser welding processes have been extensively used in Europe, America and Japan for more than 15 years. The automotive and shipbuilding industries have been major users of the fusion processes, and it has come to a point where many parameters cannot be improved any further due to limitations caused by the physics of the processes.
These fusion welding processes result in distortions of the welded plates and this becomes a problem as some welds need to be reworked. Fusion welds have inferior fatigue properties and therefore it becomes vital to find processing techniques that could improve the fatigue properties.

Friction stir welding has proved to be the best joining process for the welding of aluminium and its alloys compared to fusion-based processes. The FSW process results in defect free weld and minimum distortion of the welded plates. This process has been taken up by manufacturing industries as it eliminates defects that were apparent with other welding processes, and because the process is cost effective. The aerospace industry identified the FSW process as a “Key Technology” due to high integrity of the joint.

FSP is an emerging metal working technology that can provide localized modification and control of microstructures in near surface layer of process metallic components [Mishra et al, 2003]. This technology represents an adaptation of the principles of friction stir welding, a solid state joining process developed at The Welding Institute. The FSP process has been used to improve microstructural properties, eliminate porosity and also introduce superplastic properties in aluminium alloys.
2.2. FRICTION STIR WELDING

Although knowledge of friction dates back to antiquity, the use of frictional heat for solid-phase joining and forming techniques has only been in existence over the last century. The concept of friction was first studied around 1500 AD by Leonardo da Vinci, and more specifically by Amontons [1699] who postulated that, the coefficient of dry friction is independent of the contact area, the speed of motion, and the applied load. However, beyond normal limits, Coulomb [1779] found that with increased load the coefficient of friction increased and that it was also dependent on the speed of motion. According to Thomas et al [1998] with respect to friction-welding technology, the coefficient of friction is not in itself relevant as the conventional theory only applies to comparatively light loads with undeformed faces.

The FSW process is a relatively new welding technique invented at TWI in the United Kingdom in 1991 and patented in 1992. This technique is now in use and under study in a number of institutions around the world and involves welding both ferrous and non-ferrous metals. According to Thomas et al [1998] Friction Stir Welding has captured the attention of the fabrication industry as a solid-phase joining technique capable of good quality single sided and double sided butt "T", and lap joints.
FSW can join a number of materials, including some which are difficult to weld by conventional welding processes. One material which has proved particularly suited to FSW, is aluminium and its alloys. Kallee and Mistry et al [1999] state that FSW is like rotary friction welding, a solid phase process which operates below the melting point of the work piece material and it can weld aluminium alloys, including those such as aluminium-lithium alloys that cannot normally be joined by conventional fusion techniques. Chapter 1, Figure 1.1 illustrates features of the process, which operates by generating frictional heat between a rotating tool of harder material than the work piece being joined.

Thomas et al [1998] states that the tool is shaped with a larger diameter shoulder and a small diameter, a specially profiled probe that makes contact first as it is plunged into the joint region. The components to be welded are secured to prevent the butted joint faces from being forced apart as the probe passes through and along the seam.

The depth of penetration is controlled by the length of the probe below the shoulder of the tool. The initial plunging friction contact heats the adjacent metal around the probe as well (as a small region of material underneath the probe), but once in contact with the top surface of the substrate, the shoulder contributes significant additional heat to the weld region.
In addition the contacting shoulder, which can be profiled to provide improved coupling, prevents highly plasticized material from being expelled from the weld region. Once the rotating tool is in position the thermally softened and heat-affected region take up a shape corresponding to that of the overall tool geometry. The heat-affected region is much wider at the top surface (in contact with the shoulder) and tapers down as the probe diameter reduces [North et al, 1996].

The combined frictional heat from the probe and the shoulder creates a highly plasticized 'third-body' condition around the immersed probe and the adjacent contacting surface of the work piece top. This highly plasticized material provides for some hydrostatic effect as the rotating tool moves along the joint, which helps the plasticized material to flow around the tool. The plasticized weld material then coalesces behind the tool as the tool moves away [North et al, 1996].

In friction joining and forming the process has more relation to a fluid layer of high viscosity between solid components in relative motion and under significant compressive loading. North et al [1996] states that the thixotropic properties and the fluid flow features that occur in conventional friction welding have been reported. In some respects the science of friction processes is probably more closely allied to that of rheology.
For abutting components of similar geometry (cross-sectional area and mass) and material, an equal contribution of material from each component forms a common plasticized layer or transient 'third body'. This 'third body', in a series of infinitely thin lamina, averages 50% of the relative component velocity, effectively as a quasi-hydrodynamic intermediate zone. However material is preferentially drawn from components that are dissimilar in geometry (and/or physical material properties) as in friction surfacing, which is further augmented by the relative traverse movement. Similar differences can occur in FSW within the transient third-body plasticized region. The technology surrounding the overall tool geometry, (the probe, and shoulder profiles), and the tool altitude have been reported to be the basis of the FSW technique.

Christner and Sylva et al [1996] discovered that when process parameters are unsatisfactory, a sub-surface void or even a surface breaking defect could occur which runs parallel with the joint on the advancing side of the tool probe. Dawes et al [1995] claims that probe size and shape, in relation to rubbing velocity, and welding speed; also have a major influence on weld quality. According to Mahoney et al [1997] the effects of FSW on microstructure have been studied and for 7075 aluminium alloy were found to be less drastic than those occurring in fusion welding. Also a reduction in the grain size by dynamic re-crystallization, as well as a change from slightly elongated grains found in wrought bar, to that of more equiaxed grains is found in the weld region.
Kallee and Dawes et al [1995] claim that operating FSW under water provides increased cooling rate, leading to a reduced heat affected zone and consequent improvement in the properties of some materials. Colligan et al [1997] found that the use of fluid and/or air coolants, applied externally, or through internal spaces within, the tool has been claimed to improve traverse rates by 20-100% over that achieved without. According to Rosen et al [1996] to ensure complete penetration, or weld root closure, for FSW the bottom corners of the plates to be welded are chamfered, and subsequently filled with plasticized material from the remaining plate material.

Colligan et al [1997] states that in another method, a recessed backing plate is used so that plasticized material is extruded to form a small bead on the rear side of the work piece. Ditzel et al [1996] discovered that although preliminary, a simple heat flow model concludes that the heating during FSW occurs largely at the periphery of the tool shoulder, which conducts into the plate for bonding. According to Threadgill et al, a more comprehensive model also agrees that only the shoulder provides significant heat input, the probe’s contribution being small.

2.2.1. Process Parameters

Johansen et al [1998] claims that the main parameters of FSW are welding speed (tool displacement speed), tool rotation frequency, clamping force and tool displacement force, angle of tool inclination and its geometry.
Welding Speed

An empirical rule has been developed to determine typical friction stir welding speeds. The speed of friction stir welding is inversely proportional to the material thickness \((t)\) and dependent on the workpiece material \((\phi_{FSW})\) and the tool geometry used \((\psi_{FSW})\) [Kallee, Nicholas, Powell and Lawrence et al, 1998].

\[
V_{FSW} = \phi_{FSW} \cdot \psi_{FSW} \cdot \frac{1}{t} \quad (2.1)
\]

Table 2.1: Welding Speeds [Kallee and Lawrence et al, 1998]

<table>
<thead>
<tr>
<th>Welding Speed</th>
<th>-</th>
<th>(V_{FSW} = \phi_{FSW} \cdot \psi_{FSW} \cdot \frac{1}{t} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Factor</td>
<td>-</td>
<td>(\psi_{FSW} )</td>
</tr>
<tr>
<td>FSW Welding Speed (mm/min)</td>
<td>-</td>
<td>(V_{FSW} )</td>
</tr>
<tr>
<td>Material factor</td>
<td>-</td>
<td>(\phi_{FSW} )</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>-</td>
<td>(t )</td>
</tr>
</tbody>
</table>

According to Lawrence et al [1998] if new tool and shoulder designs are being used, the welding speed can be increased by a considerable factor. The formula is presented in Table 2.1 and the estimated welding speed calculated.
Table 2. 2: Material types [Kallee, Nicholas, Powell and Lawrence, 1998]

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Factor</th>
<th>Tool Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>3700</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium 6xxx high</td>
<td>1200</td>
<td>2</td>
</tr>
<tr>
<td>Speed trials with new design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium 6xxx</td>
<td>1200</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium 5xxx</td>
<td>700</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium 7xxx</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium 8xxx</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium 2xxx</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>Magnesium</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>300</td>
<td>1</td>
</tr>
<tr>
<td>Titanium</td>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>

TWI has developed a standard table of welding speed versus plate thickness for all materials used in the FSW process. The table can be used to choose the appropriate speed for corresponding plate thicknesses.

Figure 2. 1: Speed versus thickness [Kallee and Lawrence et al, 1998]
• **Effects of Welding Speed**

![Graph 1](image1)

From the above graphs it is evident that an increase in speed results in a reduction of grain sizes. The size of the grains is an important parameter when evaluating the strength of the weld and smaller grains are preferred. An increase in welding speed results in an increase in flow stress and a reduction in UTS [Yan, Sutton and Reynolds et al].

![Graph 2](image2)

Figure 2. 2: Welding speed versus grain size and Knoop hardness [Yan, Sutton & Reynolds]

Figure 2. 3: Welding speed versus UTS and flow stress [Yan & Reynolds]
According to Yan and Reynolds the weld nugget size decreases with increasing welding speed. Power increases with increasing welding speed which then results in a reduction in specific welding energy. The effect on nugget grain size indicates a real, but small reduction in nugget peak temperature. Welding speed effects on nugget hardness and properties are small. A higher welding speed results in narrower HAZ region and slightly increasing HAZ hardness, which indicates a weak effect of time at temperature.

Experiments carried out at NMMU revealed that welding speed is an important factor in the FSW and FSP processes. If the balance between welding speeds is not maintained the result is a poor weld. The reason being that sufficient time is needed for proper mixing (speed dependent) of the material from the plates being welded. When there is no balance between the rotational speed and feed rate the strength of the weld becomes affected and that has been the reason TWI embarked on research to determine accepted speeds for all grades of aluminium in use.
**Tool Spindle Speed**

Kaysser et al claim that the tool speed influences changes in microstructure. The rings formed by the moving tool tend to vanish with increasing tool speed. In experiments with constant ratio of rotational speed and lateral speed, no effect of speed on size and distribution of particles could be observed. Threadgill et al [1997], Dalle Donne and Ballas et al [1998] state that the heat input becomes more concentrated at higher lateral speeds. Consequently the cooling rate of the welding region also becomes higher. On this basis the increase in hardness and strength with increasing lateral speed can be explained by a partial precipitation of the hardening particles in 6 series alloys, which takes place if the critical cooling rate is exceeded. Nevertheless the loss in strength caused by the welding process is lower for the thinner sheet, resulting in almost base material strength for the highest rotational and lateral speed.

A comparison of hardness mappings for the respectively lowest speeds reveals higher maximums and lower minimums, i.e. higher hardness differences in all directions(X, Y & Z). Fatigue strength increases with higher rotational and lateral speeds for varying plate thicknesses. Joints welded at the highest speeds are even situated within the scatter band of the base material. The increase in fatigue strength with increasing weld speed is correlated to the simultaneous increase in hardness in the stirred zone.
This means that varying rotational and lateral speeds could effectively control micro structural features and mechanical properties. Yan, Sutton and Reynolds et al found that increasing rotation speed will result in higher temperature and lower plastic deformation resistance so the $F_X$ (Force in the X-direction) declines. The increasing $F_X$ force at high speeds may be related with the pressure drop behind the welding tool while the pressure in front of the tool keeps almost the same. The welding torque is believed to be related to the welding temperature through flow stress. When the temperature is low, the flow stress of the material is high; therefore the torque is high for a specific welding tool and $F_Z$ (Force in the Z-direction) force.

**Clamping Mechanism**

As high forces are applied in friction stir welding, it is necessary to restrain the work pieces to prevent movement during welding. As the tool is pushed along the weld there is a strong tendency for the plates to separate, and in thinner plates for them to lift. Correctly fixtured plates will show minimal distortion after welding, much less than shown in welds made by fusion processes. Mechanical, hydraulic and pneumatic clamping systems have all proven to work successfully. In some cases, the clamping force need only be sufficient to restrain the components whilst in others the material must be securely and rigidly clamped under high force. When welding thicker section material, the force applied by the tool and the bulk of the material are usually sufficient to prevent any vertical distortion of the joint [Threadgill and Nunn et al 2003].
Work piece clamping is an important aspect in FSW welding. If the work pieces to be welded are not held firmly, these could lead to an adverse effect on weld quality of the joints and in this case result in not having the necessary/required gap widths needed for the research. This will lead to inconsistency in the results obtained. The clamps should withstand both vertical and lateral forces imposed by the rotating tool and the moving bed; it was important that there be an equal, and an even, distribution of the clamping force on the work pieces to avoid buckling of the plates to be welded. In general, proper work piece clamping ensures uniformity and good joint quality.

**Tool Displacement Forces**

Chen and Magines et al [2002] claim that the most important factors for $F_X$ force (lateral force) are feed rate, pin length and spindle speed. The faster a tool is driven through the work piece and the longer the pin, the larger is the required force. The plunge force is not significant for $F_X$ force. Factors affecting $F_Z$ force (vertical force) include plunge depth and feed rate. For $F_Z$ force spindle speed has no significant effect as it does for $F_X$ force. The weld location has an important effect (proximity of weld to edge of plate). The factors pin length and plunge depth are related. The objective of using plunge depth as a factor is to plunge the shoulder deeper or shallower into the work piece since the $Z$-position of each tool is zeroed on the top surface of the work piece regardless of pin length; this distance must be accounted for in the plunge, so the shoulder reaches the desired location. $F_X$ force generally increases with increased
welding speed. Torque generally increases slightly with increased welding speed.

**Angle of Tool Inclination**

According to Reynolds, Seidel and Simonsen et al the tool to work piece angle for welds provides adequate forging pressure at the heel of the tool shoulder for full weld consolidation, and maintains close enough clearance between the bottom of the pin and the backing plate to promote full penetration of the dynamically recrystallized zone. Figure 2.5 shows the tool setup as found on the FSW machine.

![Figure 2.5: An inclination angle of a FSW tool [Chen & Magines, 2002]](image)

A higher tilt angle results in a larger forging action and flow in the upper zone more intensive reducing the channel type defect size. Figure 2.6 shows the influence of the change in the tilt angle during Friction Stir Welding. Cross sections of welds from experiments investigating the effect of tool tilt angle are also shown in the figure. With zero tilt angle (Figure 2.6a), the weld nugget is clearly shaped and severe bulging at the bottom (and lifting of the weld plate) of weld took place. The bulged portion became thicker (than the original thickness).
This is because, to have a 0° tilt angle, the tool shoulder was held slightly above the plate. However, the relative motion of pin/plate resulted in lifting the plate up but material around the pin in the lower portion was driven down, causing severe bulging [Chen and Magines et al 2002].

Figure 2.6: Cross section of alloy 5083 welds made using D_{shoulder} = 16mm and angle as indicated [Chen, Magines, 2002]

There was little filling in the upper zone, resulting in a wide (~5.7mm) channel (Figure 2.6a). The shearing between the weld/plate and the shoulder should still exist (particularly for the plate to have been lifted up) but forging action should be absent in this experiment. This strongly suggests that shearing due to shoulder rotation did not contribute to the plastic flow to fill the channel as forging did. That no forging action occurred in this experiment must have resulted in very little plastic flow in the upper region and hence resulted in a channel almost as wide as the size of the pin.
The width of the channel decreased as the tilt angle increased, as can be seen in the weld in Figure 2.6 (for 0, 1, 3 and 4°) and Figure 2.6b (for 2°). From a simple geometrical consideration, the increase in tilt angle increased the depth of the shoulder pressed downward and resulted in greater pushing/compressing of the material forward, meaning larger forging action. Hence, the volume of plastic flow to fill the channel became larger. This again strongly suggests that forging is the major mechanical action resulting in the plastic flow in the upper zone to close the channel [Chen and Magines et al, 2002].

The decrease in the channel width was accompanied by the weld nugget changing from more bell-shaped to more-oval shaped, when the tilt angle increased. Increasing the forging action means an increase in the applied normal force and hence high frictional force and heat. Consequently, high temperature and plasticity could be attained in the upper region and the nugget became more oval shaped when a higher tilt angle was used.

The well-defined nugget zone formed even at 0° tilt angle suggests that the tool shoulder had little influence on the actual weld nugget formation. The nugget formed due to the plastic flow induced solely by the shearing action of the tool pin. Figure 2.7 shows the change in the width of the nugget versus the change in the tilt angle. Increasing the tilt angle from (0 to 4°) increased the width of the nugget (Figure 2.7) from 7.6mm to 8.9mm ($D_{SHOULDER} = 16mm$). This, plus the fact that a more oval shape
was obtained, means that the volume of nugget increased as the tilt angle increased [Chen and Magines et al 2002].

![Figure 2.7: Width of weld nugget as a function of tool tilt angle for alloy 5083 welds made using a 16mm shoulder diameter [Chen, Magines, 2002]](image)

The previous observations clarify the importance of the tilt angle and its influence on the welded zone nugget. From this information it is imperative that a correct tilt angle should be obtained for welding in order to get a good weld. Research trends at the moment go towards using a tilt angle of 0°, and from experiments it has been possible to weld at 0° but plunge depth has to be taken into consideration in the case of FSW equipment with default plunge depth settings in their software.
2.2.2. Dwell Time

According to Johnson et al [2001], a dwell is normally made at the start of a weld to allow the material around the FSW tool to become fully plasticized, the duration being determined by experience. Experience gained at the MTRC reveals that a longer than necessary dwell time could either melt the material before the tool moves in the x-direction or reduce the time it takes to reach stability temperature by 30%. Therefore, it is necessary to get the dwell period right as it has a direct influence on the distance it takes for the weld to get to the stability welding temperature.

2.2.3. Plunge Depth

Johnson et al [2001] discovered that one of the methods of overcoming the formation of running voids during welding is to ensure that the FSW tool is correctly plunged into material. A running void is formed where there has been incomplete consolidation of the material during FSW processing, leaving a surface or sub-surface elongated void which can be caused by the selection of inappropriate FSW processing parameters or tool geometry. The importance of plunge depth has been observed during welding process at the MTRC and is emphasised in Chapter 3 where it is shown that it has a detrimental effect on the tensile strength of the welded joint.
2.2.4. Microstructural Classifications

A number of studies have been carried out on metallurgical characteristics of the friction stir welds in aluminium alloys. The typical microstructure of the transverse cross-section of the weld nugget is schematically shown in Figure 2.8.

![Figure 2.8: Weld region characterization: A; unaffected material, B: Heat affected zone, C: Thermo-mechanically affected zone, D: Weld nugget (part of the thermo-mechanically affected zone) (Copyright © 1997, TWI Ltd)](image)

The first attempt at classifying microstructures was made by P L Threadgill [Bulletin, March 1997] and the work was based solely on information available from aluminium alloys. However, it has become evident from work on other materials that the behaviour of aluminium alloys is not typical of most metallic materials, and therefore the scheme cannot be broadened to encompass all materials. The different weld regions are explained below [Threadgill et al, 1997].
**Unaffected material or parent metal**
This is material remote from the weld, which has not been deformed, and which, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

**Heat affected zone (HAZ)**
In this region, which clearly will lie closer to the weld centre, the material has experienced a thermal cycle, which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area. In the previous system, this was referred to as the "thermally affected zone". The term “heat affected zone” is now preferred, as this is a direct parallel with the heat affected zone in other thermal processes, and there is little justification for a separate name [Threadgill et al 1997].

**Thermo-mechanically affected zone (TMAZ)**
In this region, the material has been plastically deformed by the friction stir welding tool, and the heat from the process will also have exerted some influence on the material. In the case of aluminium, it is possible to get significant plastic strain without recrystallisation in this region, and there is generally a distinct boundary between the recrystallised zone and the deformed zones of the TMAZ. In the earlier classification, these two sub-zones were treated as distinct microstructural regions. However, subsequent work on other materials has shown that aluminium behaves
in a different manner to most other materials, in that it can be extensively deformed at high temperature without recrystallisation. In other materials, the distinct recrystallised region (the nugget) is absent, and the whole of the TMAZ appears to be recrystallised. This is certainly true of materials which have no thermally induced phase transformation which will, in itself, induce recrystallisation without strain, for example pure titanium, $\beta$ titanium alloys, austenitic stainless steels and copper.

In materials such as ferritic steels and $\alpha-\beta$ titanium alloys (e.g. Ti-6Al-4V), understanding the microstructure is made more difficult by the thermally induced phase transformation; this can also make the HAZ/TMAZ boundary difficult to identify precisely [Threadgill et al 1997].

**Weld Nugget**

The recrystallised area in the TMAZ in aluminium alloys has traditionally been called the nugget. Although this term is descriptive, it is not very scientific. However, its use has become widespread and, as there is no word which is equally simple with greater scientific merit, this term has been adopted. Threadgill et al [1997] suggested that the area immediately below the tool shoulder (which is clearly part of the TMAZ) should be given a separate category, as the grain structure is often different. The microstructure here is determined by rubbing the rear face of the shoulder, and the material may have cooled below its maximum. It is suggested that this area is treated as a separate sub-zone of the TMAZ.
2.2.5. Material Flow

Material flow in two friction stir welds was produced using different weld parameters and was visualised using embedded marker materials. Results of the flow visualisation show that the FSW process can be roughly described as an in-situ extrusion process wherein the tool shoulder, the weld backing plate and the cold base metal outside the weld zone form an “extrusion chamber” which moves relative to the work piece [Reynolds & Simonsen et al 1999].

Deviation from this description occurs primarily at the top surface of the weld where significant material transport occurs due to the action of the tool shoulder. The amount of material transported vertically in the weld appears to be strongly influenced by the welding temperature and hence material flow stress. There are also significant differences in the flow patterns observed on leading and trailing sides of the weld. The dashed circle in Figure 2.9 indicates the footprint of the threaded tool pin.

The white arrow indicates the position of the interface between the leading and trailing side markers (not necessarily at the weld centreline). Quantitatively the flow pattern shown in Figure 2.9 indicates several general trends in movement of material in the friction stir weld. Material near but outside the periphery of the pin on the leading side is displaced in the forward direction of welding relative to its original position [Reynolds & Simonsen et al 1999].
For any material actually in the path of the pin, the flow reverses and results in material being displaced to a position behind (relative to the welding direction) its original position. On the trailing side of the weld, material is displaced only backward. The general pattern appears to hold for most of the weld. The interface between the leading and trailing markers is out of the field of view on the top-left hand side of the picture and the dash indicates the shoulder diameter.

Figure 2.10 illustrates the action of the shoulder in forming the flow arm wherein material is transported across the weld centreline from trailing to leading side. The shoulder diameter is almost identical to the width of the deformed region as defined by distortion of the marker. The reasons for the differences in Figures 2.9 and 2.10 are probably traceable to the differences in weld temperature [Reynolds & Simonsen et al 1999].
The apparent effects of the differing weld temperatures include mixing of the marker and the base metal in the horizontal plane, and increased vertical movement of material in the weld. The continuity of flow is also evidenced by the presence of a well-defined interface between the leading and trailing sides in weld number 1 (Figure 2.10).

As such, the material is not really stirred across the interface during the friction welding process, at least on a macro level, and the process can be much more accurately described as an in-situ extrusion process than as a stirring process. It also appears that if one discounts the need to heat the material in the weld by friction, the rotation of the tool has only a secondary role to play in weld formation. The whole process may be considered as an extrusion process where the die consists of the tool (both shoulder and pin), the cold material in front of the tool, the cold material beside the tool, and the cold material behind the tool [Reynolds & Simonsen et al 1999].
The details of material flow in the weld will depend on tool rotation, particularly near the top surface where the shoulder transports a significant amount of material. However, the broad features of the process can be described without reference to the tool at all. The rotation is necessary primarily to produce heat, thereby causing a reduction of the flow stress of the material to be extruded so that it does not burst the “extrusion die”.

Having stated that tool rotation is secondary to the process outside of the necessity to produce frictional heating, it should also be stated that details of the process, which may be due to tool rotation (e.g. the flow arm), may be critical in determining the actual properties of the weldment as opposed to describing in general terms the physics of the process.

2.2.6. Joint Designs

Although the friction stir process is ideally suited for the manufacture of long straight welds, it is in fact remarkably flexible, and a variety of joints of 1, 2 and 3 dimensions have been demonstrated. The restriction of joint design is that no fillet is added, and so conventional fillet welds cannot be made [Threadgill and Nunn et al 2003]. A solution has been proposed in which the fillet is pre-extruded onto the work pieces as shown in Figure 2.11, but the practicality of this has not been demonstrated, and the solution would only be applicable to extrudable alloys such as the 6000 series, where the need for a fillet weld might be easily overcome by structure.
This point emphasises the reality that friction stir welding is an additional member of the family of mainstream welding processes. Although it may have many advantages over other processes for certain joint types, there are many cases where other processes are and will continue to be more appropriately used [Threadgill and Nunn et al 2003].

### 2.2.7. Advantages of FSW

FSW is a mechanised process with no special pre-weld edge profiling or cleaning. Russell et al [2003] claims that FSW process offers low distortion and shrinkage, and has excellent mechanical properties. In FSW there are no welding fumes or spatter hazards, no ultra-violet or electromagnetic radiation hazards. According to Pedwell, Davies and Jefferson et al [1999] the use of FSW results in weight savings, not so much from increases in stress levels and improved fatigue performance of FSW joints, but from the elimination of fasteners and butt straps used in the design of bolted and riveted joints.
The use of FSW to replace bolted and/or riveted joint designs at a given stress results in:

- Elimination of the stress concentration introduced by fastener holes;
- Improved fatigue performance through the elimination of the stress concentration;
- Elimination of interfaces between joined parts and the possibility of moisture ingress and fretting;
- Elimination of fasteners of dissimilar materials to the plates being joined and the possible galvanic action;
- Eliminates the need for sealants and local re-protection of the material.

### 2.2.8. Disadvantages of FSW

In the opinion of most researchers, the main specific defect of the joints made by FSW is lack of fusion in the weld root, which is called “kissing bonds”. Tretyak et al [2003] claims that the main causes of this defect-development are either a local thickening of the metal being welded or a disturbance of metal transfer into the root part of the joint. This defect as a rule has a very small size through the thickness so that it is extremely difficult to detect using X-ray inspection. According to Dawes et al (1995) the following may be regarded as the disadvantages of the FSW technique:
• Need for strong substrates, to which the blanks to be welded should be reliably fastened;
• Formation at the end of the weld of a hole, equal to the pin size, which is to be filled using other methods, such as welding of special plugs by the friction process;
• Application of run-on and run-off tabs to produce extended welds for the entire length of the blanks;
• Limitations for applications of the welding process in the portable variant, because of the need to fasten the blanks to the substrate;
• Lower level of welding speed, compared to mechanized arc welding for some alloy grades.

The presence of a hole may not be appropriate when welding pipes or storage vessels. The hole can be avoided by designing the tool so that the pin can be retracted automatically and gently into the shoulder, leaving behind an integral weld.

2.2.9. Industrial Applications of FSW

FSW is now being used in high volume production of aluminium automotive components at Sapa in Finspang, Sweden. They installed an Esab SuperStir™ machine, which has two welding heads to weld hollow extrusions from both sides simultaneously. The machine has a carousel-type (merry-go-round) loading and unloading station in the same line as the extrusion press.
According to Sato, Enomoto, Kato and Uchino et al (1998) in Japan, Showa Aluminium and Tokai Rubber in Oyama City joined extruded end-pieces to 2-30mm diameter tubes for the manufacture of suspension arms. The rubber of the suspension arms can be vulcanised before welding due to the low heat input of the new assembly method.

Sapa in Norway has manufactured seat structures using FSW process as shown in Figure 2.13.

Simmons wheels in Alexandria, Australia, developed a new method of producing a car wheel rim section from a rolled aluminium 6061-O sheet shown in Figure 2.14.
Russell et al [2003] claims that PDC-Teknik has managed to manufacture loudspeaker housings (Figure 2.15) using FSW process. Among the primary customers of PDC-Teknik are companies such as Bang & Olufsen (makers of audio equipment with high quality standards).

Russell et al [2003] claims that Eclipse Aviation has spent about US$300million in Research and Development programmes for the first Friction Stir Welded business jet. FSW was used in the making of circumferential and longitudinal airframe sections as shown in Figure 2.16 and Figure 2.17.
2.3. **MIG-LASER HYBRID Welding**

The first attempts to join a laser and a conventional welding torch into one welding process were performed in the late 1970s at Imperial College, London, by a group lead by William Steen. Their tests showed clear advantages of combining a plasma arc to a $\text{CO}_2$ laser process, with increases in welding speed of from 50% to 100% and of 20% increase in penetration depth as compared to pure laser welding. Reports of a more narrow and stable overall process were also given. Although encouraging, these results did not immediately spur extensive activities in the area of laser hybrid welding [Steen et al].
Probably several reasons for this relatively slow progress prevailed. Initially, the laser welding process itself had not been developed into an industrially viable process. With the development of reliable high power lasers in the 1980s and the high level of the acceptance from the industrial sectors in the 1990s, the laser welding process matured into an economic and reasonably user-friendly process. This development also clearly demonstrated the weaknesses of the laser welding process. Firstly, laser equipment is high cost tooling. The process requires stringent parts-positioning, with maximum allowable air gaps - typically in the range of 0.1 times or less the thickness of the material; this lead to large, specialized, and expensive clamping devices. Secondly, the high welding speeds lead to high solidification rates which may in turn lead to cracking or pores in the seam or in general to a more brittle structure than obtained by welding with conventional means [Bagger and Olsen et al 2004].

![Figure 2.18: A schematic of the laser-hybrid welding process.](image)
2.3.1. Process Parameters

There are probably several reasons why hybrid welding did not receive profound attention when it was discovered in the late 1970s. One reason may be that the laser welding process, due to the low heat input and narrow seam, was regarded as a kind of “ultimate” welding process. Another reason may be related to the fact that hybrid welding involves a large number of parameters. It is not only an addition of the number of parameters for the laser welding process plus a conventional process but a number of new and equally important parameters are added:

- Type of SE (Secondary Energy);
- Relative positions of laser and SE;
- Order of processing: laser or SE first; and,
- Relative energy of laser and SE.

The most important parameters and identified settings found by various researchers are presented in Table 2.3. It summarizes the characteristic features of the various types of hybrid processes.

<table>
<thead>
<tr>
<th>Process Characteristics</th>
<th>Laser/TIG</th>
<th>Laser/Plasma</th>
<th>Laser/MIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal thickness of material</td>
<td>Few mm</td>
<td>Few mm</td>
<td>&gt;3.4 mm</td>
</tr>
<tr>
<td>Ability to close gap</td>
<td>Useful</td>
<td>Useful</td>
<td>Very good</td>
</tr>
<tr>
<td>Process stability</td>
<td>High RF ignition but process stable</td>
<td>Easy ignition, very stable process</td>
<td>Requires precise wire control and attention to avoid spatter</td>
</tr>
<tr>
<td>Change in ductility</td>
<td>Can improve</td>
<td>Can improve</td>
<td>Can improve, wire alloys will be mixed with metal</td>
</tr>
</tbody>
</table>
**Choice of secondary energy source-Laser/MIG**

A metal inactive gas/metal active gas (MIG/MAG) is used to add hot (molten) material to the process. This process is used to fill a gap between two parts. Generally, a precise control of the ignition and stop of the MIG relative to the laser is required to produce a sound bead in hybrid welding. This is particularly important since extra material is supplied to the process. This also sets high demands on a precise control of the amount of material delivered to the process, i.e., the wire feed rate [Bagger and Olsen et al 2003]

**Angle of Electrode**

In conventional welding, the torch angle from horizontal is usually about 50°. The penetration depth does not increase at angles closer to vertical [Magee et al 1976].

**Relative distance between laser and SE**

The relative distance between the laser beam and the SE is one of the most important parameters to control in hybrid welding. It will be dependent on the energy supplied from each source, the type of SE, etcetera. There seems to be common ground to claim that an ideal distance is 1mm–3 mm. The values shown in Table 2.4 have been reported. As seen on the table, few researchers give other values other than 1mm–3 mm, such as 0 gap in one case [Bagger and Olsen et al 2004].
Table 2.4: Optimum relative distance between laser and secondary energy source (SE)

<table>
<thead>
<tr>
<th>Relative distance (mm)</th>
<th>Laser</th>
<th>SE</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>12kW CO2 laser</td>
<td>6-8kW MAG</td>
<td>12mm CMn</td>
</tr>
<tr>
<td>2-3</td>
<td>4.8kW CO2 laser</td>
<td>5kW GMAW</td>
<td>6mm RAEX 275 MC</td>
</tr>
<tr>
<td>0</td>
<td>5.7kW CO2 laser</td>
<td>&lt;17kW GMAW</td>
<td>Up to 25mm CSA 640.21/M</td>
</tr>
<tr>
<td>2</td>
<td>3.5KW YAG</td>
<td>3kW TIG</td>
<td>5mm AA6061</td>
</tr>
<tr>
<td>2</td>
<td>3KW YAG</td>
<td>1kW MIG</td>
<td>4mm AlMg3</td>
</tr>
<tr>
<td>2</td>
<td>3KW YAG</td>
<td>3.4kW MIG</td>
<td>5mm SS 304</td>
</tr>
<tr>
<td>2</td>
<td>1.8KW YAG</td>
<td>0.6-1.7kW TIG</td>
<td>5mm SS 304</td>
</tr>
</tbody>
</table>

Figure 2.19: Penetration Depth of Hybrid welds made with coaxial head. Positive values indicate when the laser is in front of the MIG during welding [Ishide et al,2002]

The effect on penetration when hybrid welding with a MIG torch positioned inside the focusing optics of an Nd:YAG laser can be seen in Figure 2.19. The smallest level of penetration is obtained when the MIG point of interaction is placed in the laser point of interaction. An optimum exists at relative distances of 2mm between the two. In this case, a 10% increase is seen when the laser is 2mm in front of the SE.
**Shielding Gas Type**

**Gas type for CO₂-laser hybrid welding**

It is well known that plasma absorption takes place in CO₂ laser welding. Thus, special means must be taken into account to reduce this problem; at least at power intensities above $5 \times 10^5 W/cm^2$ [Herziger et al 1986]. Plasma reduction nozzles make it possible to obtain deep penetrating welds at high power [Miyamoto et al 1984]. Coupled with low ionization gases such as nitrogen or helium, plasma absorption is reduced. In hybrid welding it has been found that up to 50% argon can be added to helium without substantially altering the depth of penetration. In tests carried out by Nielsen a 5 kW CO₂ laser and 17 kW GMAW were used.

In these tests, the addition of 4.5% oxygen was also investigated; resulting in a spray transfer condition with far less spatter, but the welding direction had to be reversed from forehand to backhand, which resulted in poorer penetration [Hyatt and Magee et al 2001]. When welding 6mm RAEX 275 MC with a 6 kW CO₂ laser and GMA, a helium content of 50%–80% seems optimum, with the remaining gas consisting of argon, CO₂ and O₂ [Nielsen et al 2002]. In conventional welding, CO₂ is commonly added in order to stabilize the arc [Hyatt and Magee et al 2001]. The addition of up to 10% CO has also been found to stabilize the CO₂ laser/GMAW process [Fellman et al 2003].
Generally, the process seems quite insensitive to the choice of gas. Helium may accentuate the formation of undercut, whereas $CO_2$ or $O_2$ flattens the bead, but prevents full penetration. It was shown that with a minimum of 30% Helium for GMAW process when $CO_2$ laser welding RAEX 650 high strength steel makes a separate helium nozzle unnecessary. Five to ten percent $CO_2$ was found to decrease undercut and reduce or even eliminate the amount of spatter. This way the oxide layer was not removed, but the amount of pores was furthermore reduced [Fellman et al 2003].

**Gas type for Nd: YAG laser hybrid welding**

Plasma absorption is not of major concern in Nd:YAG laser welding [Matsunava et al 1984]. Therefore the choice of shield gas can be determined on the shielding requirements as well as the stability of the arc. In MIG/MAG welding, optimum droplet detachment and spatter free transfer can be obtained with argon as shield gas. A low (1–5) percent of oxygen also improves droplet detachment and reduces spatter. When helium is added to the gas, a higher current is obtained, thus broadening the seam on the top surface [Hyatt and Magee et al 2001].

**2.3.2. Edge Preparation**

The preparation of edges is different in laser welding and conventional welding due to the different type of energy distribution. Because of the restricted width of the laser beam, perpendicular edges are needed in autogenous laser welding. Therefore, laser cut edges are preferred to
shear cut edges. In MIG/MAG welding, a V-shape or other angled cut is normally made prior to welding. Also using a $CO_2$ laser, a benefit has been identified of using sheared edges of 8mm Domex 390XP high strength steel. If the sheets are orientated such that the gap is in the upper part of the sheet, a better coupling of energy from a MIG source has been observed. This way, the existence of oxides on the surface has been found not to be a problem [Bagger and Olsen et al 2004].

Without the gap, weldability and weld quality is lower due to oxides [Nilsson et al 2002]. Hybrid welding with a 5 kW $CO_2$ laser and GMAW with V-shapes of 45° in wider grooves and no root opening have been shown to enable welding of 25mm depth of penetration with a four pass technique [Hyatt and Magee et al 2001].

**2.3.3. Gap bridging ability**

The ability to bridge a larger gap than in pure laser welding is perhaps the most evident benefit of the hybrid welding process. Several reports of improvements for both $CO_2$ and Nd: YAG laser hybrid welding have been published. The gap bridging ability is caused by more efficient molten flow over the gap. In PALW [Plasma Arc augmented Laser Welding technology], a joint gap increase of up to 25%–30% of the material thickness has been identified. Furthermore, a higher tolerance of beam to gap misalignment (from 0.15mm to 0.5mm at 2 m/min, 50 A) has been noted [Biffin et al 1994].
Several impressive gap-bridging abilities have been reported. For instance, it is explained how it has been possible with only a 2 kW $CO_2$, 6mm steel and 2.7kW MAG to make welds with full penetration at gaps larger than 1mm [Kutsuna et al, 2002].

![Graph showing welding speeds at various gaps](image)

Figure 2.20: Maximum welding speeds obtainable at various gap distances in hybrid butt welding [Bagger et al 2003]

The critical gap will be dependent on factors such as material thickness, laser power employed and welding speed. Figure 2.20 shows the correlation between actual gap and maximum welding speed in $CO_2$ laser/MIG welding of 2.13mm CMn steel. The sheet edges in these tests were ground. Here, a gap larger than 0.1mm was not realistic in laser welding. In hybrid welding, a welding speed of 3.5 m/min was still maintained at a gap of 0.6mm [Bagger et al 2003]. The presence of a gap seems to improve the quality when welding aluminium with an Nd: YAG laser combined with a MIG source.
When welding 5mm AA5083 at 4 kW +3 kW with a 0.6mm gap, the speed could be increased twofold as compared to welding with zero gap and the number of pores was significantly reduced [Nielsen et al 2002]. No machining of groove edges was performed, illustrating that the process should be regarded more as a laser welding process than a conventional process.

In these tests it was furthermore shown that T-joints and fillet joints with gaps of 1mm in 2.5mm mild steel and gaps of 0.6mm in fillet welding of 2 mm aluminium at 7 m/min could be realized, (see Figure 2.21 and Figure 2.22).
2.3.4. Weld Penetration

One of the reasons for the deeper penetration as well as increase in welding speed of the hybrid welding process compared to pure laser welding is the higher amount of energy delivered to the work piece. Another reason may be the better absorption of laser energy when heat is added from the SE [Albright et al 1982]. The added heat and temperature will reduce the reflectivity. For instance, Biffin and Walduck et al [1994] reported a 50% increase in penetration of 0.6mm stainless steel at 400W $CO_2$ laser and the PALW process.

This is particularly advantageous when welding highly reflective materials, where the $CO_2$ laser light has a lower absorptivity than in welding of steel. Aluminium is a material that is not easily welded by $CO_2$ laser. Biffin and Walduck et al [1994] reported stable welding at 0.5 m/min in 0.6mm with a $CO_2$ coupled to a PALW. Another effect of the arc in hybrid welding is the ability to remove oxides on the top surface, again enabling a better coupling of laser light into the material [Diebold et al, 1984]. The possibility of increasing the weld penetration in hybrid welding as compared to pure laser welding has been presented by Matsuda et al [1988]. Here, trials conducted with a 5kW laser and 5 kW GTAW in welding of 12mm mild steel improved penetration by 1.3 - 2 times. On the other hand, reports of no improvement have also been given by Nielsen et al [2002].
Figure 2.23 demonstrates the overall performance of the Nd: YAG/TIG hybrid welding process at different welding speeds. In the range 6 to 12 mm/min, the penetration of hybrid welds is deeper than YAG welds and TIG welds respectively. As the speed increases, the difference in penetration between hybrid and laser welds becomes smaller.

![Comparison of penetration depths for various welding processes](Naito et al 2002)

### 2.3.5. Welding Speed

Probably the second most interesting feature of the laser hybrid welding process is the reporting of increased welding speed as compared to autogenous laser welding.

**CO₂ - laser hybrid welding**

The PALW process [Biffin and Walduck et al 1994] has identified that hybrid welding is 2–3 times faster than laser welding with identical fusion characteristics, but with a larger grain size and heat affected zone (HAZ) (due to increased heat input). A 400 W CO₂ laser was used to weld 0.6mm stainless steel.
Nilsson et al [2002] explains that in general there is no increase in speed with the hybrid process when the edges of 8mm mild steel are milled or laser cut. Using sheared edges (gap on top) instead of laser cut increased the speed by 60% for the hybrid process. Kutsuna [2002] has reported an increase of 30% when welding with a 2.4kW CO₂ and a 4800 W MAG as compared to pure laser welding.

**Nd: YAG laser hybrid welding**

In Nd: YAG/TIG welding of 2mm AlMg₃ with 1.9kW laser power the welding speed could be increased from 5 to 8 m/min [Dilthey et al 1999]. Nearly the same welding speed as pure laser welding was observed in lap welding of 0.8–1.6mm zinc coated mild steel with a 4.5kW Nd:YAG laser and MAG [Nilsson et al 2002].

**2.3.6. Weld Quality**

Beside the better ability to bridge gaps and the deeper penetration depths reported as a result of combining a conventional welding process with a laser source, a number of improvements in the weld qualities have been reported. This includes reduction of pores and cracks and improvements in ductility [Bagger and Olsen et al 2003]. These are described in the following sections.

**Pore Reduction**

One of the problems when welding aluminium with a CO₂ laser is the often large amount of pores created. By combining a 12 KW CO₂ with a 3
kW MAG, the amount of pores in AA5083 has been significantly reduced, even with air gaps of up to 0.6 mm [Nielsen et al 2002]. When welding stainless steel AISI 304 with Nd: YAG lasers with 1.3 kW [Ishide et al 2002] and 1.7kW [Naito et al 2002] coupled to TIG sources, the use of argon shield resulted in either complete elimination [Dilthey et al 1999] or clear reduction [Naito et al 2002] as observed in Figure 2.24 amount of pores.

This may be explained either by an enlarged keyhole (entrapped shielding gas can more easily escape) or by intense evaporation induced by arc concentration near the keyhole surface (shielding gas is prevented from entering into the material). Another application where hybrid welding has improved the overall quality is in welding of zinc coated steel. When arc welding is performed after laser welding in the lap joint configuration, the zinc vapour has sufficient time to escape out of the molten metal and the result is that no blowholes are created [Nilsson et al 2002].

**Crack Reduction**

Typically, an Nd: YAG laser is employed for laser welding of aluminium. By combing a 3.5kW Nd: YAG with a TIG torch, [Fujinaga et al 2002] a complete elimination of cracks in 10mm A6061 with an effective penetration of 6–8mm, has been reported.
Change in ductility

It is well known that laser welds in, for example, mild steel becomes harder than the base material due to the high solidification rates experienced during cooling. This may have implications that limit the use of high power lasers for welding.

For instance, a high hardness is unfavourable when laser welded tailored blanks are to be formed, since the formability of a blank is considerably reduced in the strain range due to the laser weld [Bagger & Rasmussen et al 1998]. Ductile welds are also of utmost importance in welding of, for instance, heavy section parts in ships [Kristensen et al, 1999].

The use of the hybrid welding process seems to be a useful way to improve the ductility as compared to entirely laser welded parts. The hybrid processes laser/plasma and laser/MIG resulted in clear improvements in the ductility of the high strength steel CMn, with reductions in hardness values compared to pure laser welding of 27% and 33%, respectively [Bagger & Olsen et al 2003].
**Heat input**

The disadvantage of using the hybrid welding technique is the added amount of heat to the material compared to pure laser welding. If the welding speed cannot be increased proportionally to the increase in energy, an increase in heat input per welded length will follow, perhaps compromising the geometrical configuration or overall parts tolerances. An example of the effect of heat input is shown in Figure 2.24 for a CO\textsubscript{2}/plasma process at 1.8kW laser and 1kW plasma. In this case the seam increased 90% in width, but maintained a very cosmetic top surface [Bagger & Garner et al 2001].

![Figure 2.24: Example of seam appearance in CO\textsubscript{2} laser welding (top) and laser/plasma welding (bottom) [Bagger & Garner et al 2001]](image)

One correlation between heat input and obtained penetration depth is shown in Figure 2.25 for a GMAW, laser and hybrid laser gas metal arch welding (LAGMAW) welds. The welds produced by the hybrid process required less total heat input to produce a given weld penetration than the GMAW welding process alone. This is particularly evident for producing 8mm deep welds [Hyatt and Magee et al 2001].
2.3.7. Industrial Applications

Over the past few years, the hybrid welding process has seen its entrance into industrial applications. As the development in this field has attained a high pace, the following few industrial applications have been chosen entirely to illustrate practical solutions. The presentation does not intend to cover all solutions realized. Two major businesses that have established hybrid welding systems in preproduction or production are the automotive industry and the ship building industry.

The automotive industry is a high volume industry, whereas the ship building industry is characterized by having many kilometers of welds in each ship. In the automotive industry, the main advantage is the higher gap-bridging ability that the hybrid welding process has compared to the laser welding process alone.
At Volkswagen, elimination of a pressure wheel for holding the sheet in place has also been made possible with the introduction of hybrid welding. Furthermore, high quality fillet and butt welds are possible in aluminium. In each Phaeton car manufactured, 7 MIG welds, 11 laser welds, and 48 hybrid welds, are made with a total seam length of 4980mm [Staufer & Miessbacher et al 2003].

Figure 2.26: Integrated hybrid welding developed by Fronius [Graf & Staufer et.al 2003]

Figure 2.26 shows the welding torch used. With this, mild steel, stainless steel, and aluminium with thicknesses of 1-4mm can be welded with 3kW of Nd:YAG power. Compared to welding with pure laser energy, 1kW of laser power is saved with the hybrid technology (approximately 100 000 Euros), but an additional MIG equipment with a price of 40 000 Euros needs to be added. At Meyer Werft, a German ship yard, a 12kW CO₂ laser has been coupled to a GMA welding unit in a so-called preproduction installation.
Up to 20-metre long seams have successfully been made in 12mm thick fillet joints. Process qualification for approval of the hybrid welding process has been based on hardness measurements, tensile tests, notch impact tests, transverse and side bending tests, cross tensile tests, as well as fatigue tests. All these tests showed satisfactory results [Roland & Reinert et al 2002]. An automatic hybrid welding demonstrator installation for fabrication of high precision lightweight structural shapes for shipbuilding and other industries has been published by Orozco et al 2003. The system comprises a 25kW CO₂ laser, 6kW GMAW, a 12m long gantry, seam tracking and gap distance monitoring, welding quality monitor, and process control software.

Good quality welds in A-36, Dlt-36, HSLA-65, and super austenitic Stainless Steel AL6-XN have been made. Speeds of between 1.9 and 2.5 m/min have been possible in 12mm thick material with full penetration welding. A production system for hybrid welding of telescopic lifters has been made in Finland [Jenstrom et al 2002]. It consists of a 6kW CO₂ laser and GMAW working on up to 6 m long, and square pipes of RAEX 650 with material thickness of 4mm. The main reason for implementation of this system is the ability of the hybrid welding process to fuse together gaps of up to 1mm. With this system, basic investigations showed that a separate coaxial nozzle arrangement for plasma reduction was not required.
Instead, a minimum of 30% Helium was added at 25–30 l/min to the GTAW nozzle. The GTAW was placed so that it interacted with the sheet 3mm in front of the laser.

### 2.3.8. Advantages of the Hybrid process

Some of the advantages of using a hybrid process are:

- Increased penetration;
- Increased welding speed;
- Reduced heat input;
- Improved tolerance to poor fit-up;
- Reduced equipment cost, as a lower power laser can be used;
- Better energy coupling.

### 2.3.9. Disadvantages of the Hybrid process

There are some potential disadvantages:

- The hybrid process is a complex process with more variables when compared to the individual processes. The additional parameters include:
  - Distance between laser spot and MIG/MAG wire;
  - Ratio between laser and MIG/MAG power;
  - MIG/MAG leading or following;
  - Angles of MIG/MAG torch and laser beam;
  - Process parameters cannot necessarily be directly inferred from separate processes.
2.4. TOOL DESIGN

2.4.1. Introduction to Design

Dieter et al [1986] states that although engineers are not the only people who design things, it is true that design is to “fashion after a plan”, but that leaves out the essential fact that design is to create something that has never been. Certainly an engineering designer practises design by that definition, but so does an artist, a sculptor, a composer, a playwright, or many another creative members of our society. The professional practise of engineering is largely concerned with design; it is frequently said that design is the essence of engineering. To design is to pull something new or arrange existing things in a new way to satisfy a recognised need in society.

An elegant word for “pulling together” is synthesis. According to Blumrich "Design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way." The ability to design is both a science and an art. The science can be learned through techniques and procedures, but the art can be learned only by doing design. A design is produced to satisfy a need that someone has. It is something that has not always existed; instead it is created expressly to satisfy a need. Good design requires both analysis and synthesis. In order to design something we must be able to calculate as much about the thing’s
behaviour as possible by using the appropriate disciplines of science or engineering science and employ the necessary computational methods. *Analysis* usually involves the simplification of the real world through models. It is concerned with placing/putting/simplifying the problem into manageable parts, whereas *synthesis* is concerned with assembling the elements into a workable whole [Dieter et al 1986].

**Design process steps**

According to Dieter et al [1986] the design process consists of the following steps:

- Recognition of a need;
- Definition of a problem;
- Gathering of information;
- Conceptualisation;
- Evaluation;
- Communication of the design.

The design process generally proceeds from top to bottom in the above list, but it must be understood that in practise some of the steps will be carried out in parallel, and that feedback leading to iteration is a common fact of design. According to Krick et al [1976] the process of design embraces the activities and events that transpire between the recognition of a problem and the specification of a functional, economical, and otherwise satisfactory solution to that problem. Design is the general process by which the engineer applies his knowledge, his
skills, and his point of view in the creation of devices, structures and processes.

2.4.2. Design Process for FSP

Recognition of a need

Friction stir welding is a new joining technology that is being pursued by several industry sectors to enhance material properties, improve machinability, and to boost affordability to meet ever increasing design requirements for new products. The "need" was to design a FSW tool for root dressing (Friction Stir Processing) and at the same time improve microstructural characteristics at the weld surface, which would then lead to improved mechanical properties of the weld. The geometry of the probe is important as it ensures sufficient working of the material at the weld line and controls material flow around the probe and under the shoulder to form a satisfactory weld.

- **Probe length and diameter:** The length of the pin controls the amount of material to be stirred and only 50% of the plate had to be affected by the stirring action for this research. The diameter of the probe was based on the thickness of the bead to be root dressed.

- **Shoulder diameter:** Shoulder diameter was based on the diameter/pin ratio developed by TWI for the conventional tool design. The root bead also played a role in the final diameter of the shoulder.
General design goals such as safety, environmental awareness, reliability, performance and ease of use, acceptable cost, etcetera, usually associated with any design, were considered:

- **Environmental awareness**: In FSW there are no welding fumes or spatter hazards, no ultra-violet or electromagnetic radiation hazards. Plates welded by the friction stir process could be recycled without any problems.

- **Reliability**: The FSP tool depends on the operator to feed in the correct machine operating parameters on the control system. Research has proved that one tool can weld up to 1000 meters. If the correct heat treatment method was used for the tool, a longer tool life is guaranteed.

- **Performance**: The tool designed performed excellently as tensile data from trial tests was compared to the work of Ericsson [2002] and Sandstrom [2002]. Speeds relevant to the material (6082-T6) welded were considered as researched by Johnson [2001].

- **Size**: The dimensions of the tool were based on existing tool designs and the weld beads to be root-dressed by the FSW process. The aim was to perform root dressing [FSP] and the thickness of the plate was also considered.

- **Cost**: The tool had to be as simple as possible but at the same time address the root dressing problem [FSP]. 80% of the machining was carried out at the university to cut down on manufacturing costs.
• **Safety:** Compared to other joining operations FSW is the safest proven method at present.

**Definition of a problem**

When there is a change in tool design, aluminium alloy, joint type or joint thickness, the weld properties also change. The design had to be able to perform FSP on the MIG-laser hybrid welded root beads of aluminium alloy plates with varying gap widths. The objective was to improve on the existing knowledge of the combined Friction Stir and MIG-Laser Hybrid welding processes and determine the effect Friction Stir Processing had on the mechanical and metallurgical properties of 6082-T6 aluminium alloy plate.

**Design requirements**

It would seem obvious that, to be satisfactory, the design should meet the required performance specification. Development of the performance specifications is the major task in problem definition. This is the critical stage in design; for if it is done skilfully, it will aid greatly in producing a superior design. A common failing in problem definition is to overemphasize the specification of certain property values and performance parameters.

The design is then forced to take a predetermined path. A better approach is to specify the functions the design should have so that the
creativity of the designer is not hampered at the outset [Dieter et al 1986]. The Friction Stir Processing tool had to fulfil the following design requirements:

- **The maximum diameter of the probe**: The maximum bead width of the received MIG-Laser hybrid welded plates was 7mm and therefore the probe diameter had to be equal to the maximum bead/root width;

- **The maximum length of the probe**: The plates to be root dressed had already been welded by the MIG-Laser Hybrid process and the objective was to remove the root/bead formed by the mentioned process. With the thickness of the plate at 6mm the aim was to friction stir process 50% of the plate, that is the probe had to be ± 3mm long;

- **The maximum diameter of the shoulder**: The shoulder diameter was based on the pin/diameter ratio (2.5) developed by TWI and depended on the pin diameter. The pin diameter also played a role in the final size of the shoulder diameter;

- **Tool fit**: The new tool had to fit into the existing tool holder of the FSW machine;

- **Thermocouple hole**: A thorough hole had to be drilled for the thermocouple insert;
• **Heat treatment**: The new tool was made using W302 (H13) tool steel and heat treated up to HRc 52-56.

**Thermal treatment of W302 (H13)**

*Calvin Blignault et al 2002*

Since the FSW tool has a very specific tempering phase, great precaution had to be followed during the heat treatment stage in order to produce a high quality tool. Four specimens with exact dimensions, but different probe geometries, were prepared to be tempered. The specimens were heat treated following specifications supplied by Bohlersteels in order to produce the required hardness:

• **Stress relieving**: 500°C to 550°C Slow cooling in furnace; intended to relieve stresses set up to be extensive machining, or in complex shapes. After thorough heating, hold in neutral atmosphere for two hours;

• **Hardening**: 1020°C to 1080°C Oil, salt bath (500°C to 550°C), air holding time after temperature equalization: 15 to 30 minutes; Obtainable Hardness: 52-54 HRc (Oil or Salt Bath), 50-54 HRc (Air);

• **Tempering**: slow heating to tempering temperature immediately after hardening time in a furnace. One hour for each 20mm of work piece thickness but at least two hours cooling in air. It is recommended to temper at least twice.
A third **tempering cycle** for the purpose of stress relieving may be advantageous. **1st Temper**: Approximately, 30°C above maximum secondary conditions; **2nd Temper**: Temper to desired working hardness; **3rd Temper**: For stress relieving at a temperature 530°C - 550°C.

**Heat treatment procedure**

1. Specimen in furnace: 30 minutes at 1050°C - Actual time 25 minutes at 1050°C from equalization.
2. Quench in oil directly after heating.
3. **1st Temper**: Placed in second furnace equalization temperature at 530°C - Actual time 1hour.
4. Cool in air for 2hours.
5. **2nd Temper**: Place in furnace equalization temperature at 600°C - Actual time 1hour.
6. Cool in air for 2 Hours.
7. **3rd Temper**: Place in furnace equalization temperature at 550°C - Actual time 1hour [Calvin Blignault et al 2002].

2.4.3. **Gathering of information**

**Tool function**

According to Threadgill and Nunn et al [2003] the tool is the essence of the process, and performs a number of functions. If the tool design or material is not right, the quality of the weld is likely to be poor. In designing any tool and specifying tool materials, it is essential to realise
that the shoulder and the pin perform different functions. The tool must undertake the following:

- Heating and softening the work piece material;
- Dispersing the oxide layers in the joint;
- Extruding material from front of tool to back;
- Extruding material from top to bottom of joint;
- Consolidating softened material to form solid phase joint;

In order to do this, the tool material must have certain essential and ideally additional desirable properties.

**Tool properties**

- **Strength at service temperature**: at present the strength levels required cannot be easily predicted, and requirements are based on experience.
- **Wear resistance**: wear may occur by various processes and there is no simple test, other than making a weld that will allow the wear performance of prospective tool materials to be predicted.
- **Creep resistance**: extended service at high temperatures and forces could cause creep damage, although this has not been reported specifically in the appropriate literature.
- **Fracture toughness at ambient and elevated temperatures**: shock loading can occur for example at the tool touchdown event, or perhaps due to some unexpected event during welding. Failure
to withstand such shocks can lead to tool failure and often challenging weld problems.

- **Ability to be processed into complex shapes**: experience to date suggests that thicker work piece materials require more complex tool shapes.

- **Good friction couple**: this is particularly important in the early stages of the weld, when generation of heat is primarily by friction between the tool and the work piece.

- **Thermally stable**: many materials will anneal or over-age at elevated temperatures.

- **Inert with work piece material**: some work piece materials may react with certain elements in the tool material. A good example is titanium, which forms low melting point eutectics with nickel, cobalt and iron. These have melting points in the range 1000°C to 1200°C temperatures which can be reached during welding.

**Tool geometry - Probe Profile**

According to Dawes et al (1998), the main function of the probe is to ensure sufficient working of the material at the weld and to control the flow of the material around the probe and underneath the shoulder to form a satisfactory weld. The probe generally has a flat or re-entrant fluted shape profile. Preferably, the probe has an odd number of equally spaced flats or flutes to maintain maximum cross-section opposite to the ridge lands. These flat or re-entrant features reduce the probe volume and provide a suitable swept volume to static volume ratio. The greater
the volume ratio the greater the path for material flow and the more efficient is the probe.

In addition, these re-entrant features, especially the helical coarse ridges around the lands, help break up and disperse the surface oxides within the joint region. For lap welding, a probe has been developed to provide a wider region and also help avoid problems associated with upper thinning at the lap weld interface. Provided a certain minimum probe tip diameter is maintained, the frustum shape requires less effort to traverse it through the plasticized material than a cylindrical probe. This gain in welding performance is due to the reduction in probe volume and its design features [Thomas & Gittos et al 1999].

It should also be noted that all re-entrant features, especially the change in section between the shoulder and the probe, are well radiused in order to reduce stress concentration and thereby fracture of the tool. To enable more effective flow of the plasticized material, it is preferred that the distance between each ridge be greater than the thickness of the ridge itself. The Whorl™ concept provides for probe cross-sections that are circular, nominally oval, flattened, or re-entrant. In this way, the probe displacement volume is less than its volume of rotation. The combined use of a helical ridge and re-entrant features means that these types of probe further enable the easier flow of plasticized material. In addition, the inclination of the continuous spiral ridge can be designed
and manufactured to suit the material being welded. Variation in the inclination of the spiral ridge allows adjustment to the degree of stirring and the downward movement of the plasticized material.

For Whorl™ and MX Triflute™ probes, the downward thrust and rotation (as viewed from underneath the shoulder) are in a clockwise direction for a right hand spiral, and vice versa. Friction stir welding probes are subjected to cyclic bending (similar in nature to a rotating cantilever) and torsion loads. Both probes are more uniformly stressed during welding and allow for a more efficient flow path than the conventional cylindrical pin type probe. The probes generally have a profiled or threaded surface to facilitate the downward augering effect. Preferably, they have an odd number of equally spaced flutes to maintain maximum bending strength opposite to any re-entrant feature. Figure 2.27 shows cross sections of probe profiles.

![Figure 2.27: Illustration of three and four fluted probe profiles of the same cross-sectional area (Copyright © 2001, TWI Ltd)](image)
**Tool geometry - Shoulder Profile**

According to Thomas and Dolby et al, [1998] the shoulder compresses the surface of the work piece and contains the plasticized weld region. Heat is generated on the surface by friction between the rotating shoulder and the work piece surface and, when welding thin sheets, this is the main source of heat. As the work piece thickness increases more heat must be supplied by friction between the rotating probe and the work piece surface and, when welding thin sheets, this is the main source of heat.

Thomas et al [1998] and Gittos et al [1999] agree that shoulder profiles are designed to suit different materials and conditions as necessary. These shoulder profiles improve the coupling between the tool shoulder and the work piece by entrapping plasticized material within special re-entrant features. This essentially provides like-to-like frictional contact and improved weld closure by helping prevent plasticized material from being expelled. Examples of different shoulder profiles concepts are shown in Figure 2.28.

![Figure 2.28: Tool shoulder geometries, viewed from underneath the shoulder (Copyright © 2001, TWI Ltd)](image)
2.4.4. Conceptualisation

Existing concepts

The concepts shown in Figure 2.30 are a result of intensive FSW research at TWI and the advantages and disadvantages were considered. Different tools perform differently due to their design geometry and welding parameters. Parameters good for one tool do not necessarily produce good results when another tool is used and the same applies to aluminium grades used in the FSW process. Most tool concepts designed are for butt and lap joints but differ in probe design. For butt welding one gets a tapered or a parallel probe and for lap a tapered as shown in Figure 2.29.

![Figure 2.29: (a) Typical probe design for butt welding tool, (b) Typical probe profile for lap welding tool](Figure 2.29: (a) Typical probe design for butt welding tool, (b) Typical probe profile for lap welding tool (Copyright © 2001, TWI Ltd)
When designing a tool for the FSW process more emphasis is placed on shoulder and probe profiles as they have a direct influence on the weld profile. The more complicated and advanced probe profiles require a lot of capital investment in the manufacturing process.

**Concept 1 (MX Triflute™ Tool)**

![MX Triflute™ Tool](image)

This tool is one of the more successful designs to have been developed at TWI. In this design, three deep helical grooves are cut into the pin of the tool. This has the advantage of improving downward motion of the softened material. The presence of the deep flutes provides an easier path for the softened material from the front of the tool to the back, while still maintaining a stiff structure. As the pin is a cantilever subjected to bending forces, it is important that the pin should not bend significantly [Threadgill & Nunn et al 2003]. The Triflute™ tools were designed to give an even more efficient flow path than that of the whorl. The Triflute™ has about 74% less volume than the conventional tool.
The configuration of the Triflute™ gives it a more uniformly stressed tool. The MX Triflute™ tool further incorporates a helical ridge around the triflute lands [Thomas & Gittos et al 2000] and this reduces the tool volume and therefore aids material flow. The re-entrant helical flutes and threads features used on the probes increase the surface area of the probe. This means that the interface between the probe and the plasticised material is also increased.

**Concept 2 (Conventional Tool)**

![Concept 2 (Conventional Tool)](Copyright © 2003, TWI Ltd)

Very early work used a cylindrical pin beneath a cylindrical shoulder, but such simplistic tool designs are of little use in materials such as aluminium which readily soften. The first successful tool was called 5651 design, basically a parallel-sided threaded pin with a rounded tip and a small angle on the shoulder. The tool is normally tilted by 2 to 3 degrees to allow extra force to be applied to the weld to prevent void formation. The tool has proved to be very reliable, and most applications in production at the time of writing are believed to be based on the design, or a close derivative.
It is claimed for example that the use of a tapered rather than a parallel threaded pin can offer advantages in welding speed [Threadgill and Nunn et al 2003]. The conventional tool is a non-linear extrapolation from the shape and dimensions of the tool with a cylindrical threaded pin and a scrolled shoulder previously used by Dawes for welding 6.4mm material [Dawes, Spurgin and Staines]. The conventional tool design is mostly used when welding thin plates and these tools are even more useful to research institutions starting or setting up Friction Stir Welding centres. The conventional tools help in the understanding of basic FSW principles and it is from these tools that advanced tools have been developed.

The conventional tool is cheap and easier to make because of the uncomplicated probe/pin design. For mass production it is advised to use tools developed at TWI as they have enough information on each tool design and the best suitable application for the tool. The information includes welding speeds, plate thickness, grade of aluminium and feed rates to be used for the given tool. According to Threadgill et al [2003] these tools have some drawbacks which restrict the use of the process in many potential applications. These are as follows:

- The tool must be tilted away from the direction of travel by typically 1° to 3° in order to provide a compressive downward force behind the tool which helps consolidation of the material as it cools;
• The use of a tilt angle makes it difficult to make non-linear welds as complex steering of either the tool or the base carriage or the base plate which is required in order to keep the angle of tilt parallel to the welding direction;

• With a zero tilt angle, only a simple X-Y movement on either the carriage or the base plate would be required.

**Concept 3 (Whorl™ Tool)**

![Figure 2.32: The Whorl™ tool (Copyright © 2003, TWI Ltd)](image)

With the Whorl™ tool the shoulder profile is designed to provide better coupling between the tool shoulder and the work piece. This provides like to like frictional contact and improved weld closure by helping prevent plasticized material from being expelled. Improved coupling is achieved by entrapping plasticized material within special re-entrant features, such as scoops and concentric grooves. The shoulder profiles with concentric grooved rings provide improved movement of the top surface layers of the work piece plasticized material.
Combined rotation and travel means that these concentric ring grooves provide a series of continuous cycloidal paths each with a large overlap. The Whorl™ tools are designed such that the probes are not parallel sided but frustum-shaped. Such a shape displaces substantially less material during welding than the cylindrical pin (up to 30% less). Furthermore, a coarse auger thread is employed which further reduces the displaced volume to 61% and which again facilitates flow of material past the tool during welding. All Whorl™ tools incorporate concentric rings on the tool shoulder to entrap plasticized aluminium on the weld surface [Thomas & Gittos, 2000]. The Whorl™ tool shape ensures that the lower surface of the helical ridge provides a clear downward augering force, with less interference from the next ridge below.

The core of the probe need not run parallel with the helical ridge, nor does the ridge have to be of uniform pitch. In this respect, the helical ridge is not a simple external thread, which has to engage with an internal thread, but is essentially an auger that is immersed in the plasticized medium which the tool creates. To enable more effective flow of the plasticized material, it is preferred that the distance between each ridge is greater than the thickness of the ridge itself. The Whorl™ concept provides for probe cross-sections that are circular, nominally oval, flattened, or re-entrant. In this way, the probe displacement volume is less than its volume of rotation. The combined use of a helical ridge and re-entrant features means that these types of probe further enable the easier flow of plasticized material.
In addition, the inclination of the continuous spiral ridge can be designed and manufactured to suit the material being welded. Variation in the inclination of the spiral ridge allows adjustment to the degree of stirring and the downward movement of the plasticized material [Thomas, Nicholas and Smith et al 2001].

**FSP Tool concept**

![Figure 2.33: The FSP Tool Concept](image)

The tool concept is based on the conventional tool as designed by TWI. This can be seen on the shoulder and pin profiles. A major factor in achieving good welds and process efficiency with the friction stir welding process is in the design of the shoulder and the probe. According to Dawes et al [2000] with conventional FSW tools, the dynamic to static ratio volume is achieved by the design of the probe geometry, and for all conventional tools the flow path relies on the re-entrant features of the probe within the rotational diameter. The tool concept was designed to move across an already welded joint region of the MIG-Laser hybrid welded plates to create a fully recrystallized, porosity free, fine grained microstructure. The design of the tool concept includes features found in
conventional and A-skew™ tools from which it is based but with minor differences in the shoulder and pin profiles.

![Image](image1.png)

**Figure 2.34: The Skew™ tool (Copyright © 2003, TWI Ltd)**

The probe consists of a threaded profile with one flute running parallel to the pin on one side. The flute improves the flow path of material during welding and also assists in the mixing of material of the plates being welded. The shoulder contains a groove that helps entrap plasticized aluminium on the weld surface. The shoulder compresses material from the root and mixes it back within the joint region and excess material becomes side flash as it has nowhere to go if it has not been compressed. The shoulder also provides additional frictional treatment to the work piece as well as preventing plasticized material from being expelled from the weld surface. The tool concept is designed not to weld per se but to improve the mechanical properties of an already welded joint. The FSW process is a complex process and any change in the weld parameters could influence joint integrity. The FSW tool geometries are summarized in the Table 2.5 (Adapted from Johnson).
Table 2.5: Tool geometry developed for FSW tools

<table>
<thead>
<tr>
<th>Tool</th>
<th>Shoulder Diameter (mm)</th>
<th>Centre Pin Diameter (mm)</th>
<th>Pin Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>25</td>
<td>10</td>
<td>6.1</td>
</tr>
<tr>
<td>K2</td>
<td>25</td>
<td>8</td>
<td>5.8</td>
</tr>
<tr>
<td>K3</td>
<td>20</td>
<td>8</td>
<td>5.8</td>
</tr>
<tr>
<td>K4</td>
<td>20</td>
<td>9</td>
<td>6.15</td>
</tr>
</tbody>
</table>

This geometry was developed in the TWI Group Sponsored Project 5651 to become the standard FSW tool design for many fabrication companies and is still widely used for welding plate up to 10mm in thickness.

Table 2.6: Tool dimensions

<table>
<thead>
<tr>
<th>Tool</th>
<th>Shoulder Diameter (mm)</th>
<th>Centre Pin Diameter (mm)</th>
<th>Pin Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3</td>
<td>15</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>G2</td>
<td>25</td>
<td>10</td>
<td>5.8</td>
</tr>
</tbody>
</table>

As can be seen in Table 2.6 the ratio of pin to shoulder diameter varies from 1:2.5 to 1:3. Therefore when a tool is to be designed one has to design within these limits. Based on the maximum root/bead width which was 7mm and the tapered shape of a MIG-Laser hybrid welded nugget region, a pin diameter of 6mm was chosen and the shoulder diameter 15mm resulting in a ratio of 2.5mm. Tool G2 is the main FSW tool at the MTRC used to weld 6mm thick plates whereas tool G3 has been specifically designed for FSP to weld just 3mm of the 6mm thick plates. In a way the new tool would cause a change to the nugget region’s structure, thereby influencing the microstructure.
It was evident that by welding on the joint with the Friction Stir Processing tool, the size of the nugget region would increase and probably result in an increase in joint strength. The tool concept is designed to weld on only 50% of the plate thickness on the already MIG-Laser hybrid welded plates. According to Sorenson and Posada et al [2003] a combination of grain refinement and porosity healing has led to an improvement in mechanical properties of fusion based iron-based alloys. It is envisaged that the chosen tool concept will have a positive influence on mechanical and metallurgical properties on the welded joint. The FSP tool concept showed in Figure 2.33 would be used to carry out Friction Stir Processing on the aluminium plates.

### 2.4.5. Communication of the design

According to Dieter et al [1986], it must always be kept in mind that the purpose of the design is to satisfy the needs of a customer or client. Therefore the finalised design must be properly communicated, or it may lose much of its impact or significance. Detailed engineering drawings, computer programs and working models are frequently part of the deliverables.

### 2.5. FATIGUE

**Factors affecting fatigue**

Scratches, small marks and other imperfections on the surface of a fatigue test specimen will cause a decrease in the fatigue life of the material. It is important that an effort should be made to eliminate some
of these imperfections. Corrosion should also be avoided on the fatigue samples as small pits may form on the surface of the material, producing an effect similar to that caused by etching. It should be noted that all fatigue samples are machined, with shape characteristics that maximise the fatigue life of the metal, and highly polished to provide good surface finish characteristics which enable the best fatigue life. The surface finish is a very important aspect in fatigue testing as most failures start on the surface. The reason being that the most highly stressed fibres are located on the surface and the intergranular flaws which precipitate tension failures are more frequently found at the surface.

2.5.1. Crack Propagation

Once a crack is present in a material, it will tend to grow under the influence of cyclic loading. The crack may be initiated by fatigue, or may be pre-existing from manufacture, or may be caused by an impact, or similar event (e.g., a thermal shock.) The crack will grow to a critical length after which fracture of the component will occur.

2.5.2 The S-N curve

The first systematic and quantitative investigation of fatigue damage was provided by August Wohler in 1858 and has resulted in the widely known Wohler curve, or S-N curve (i.e., stress(S) versus number(N) of cycles to failure). This curve conveniently displays basic fatigue data in the elastic stress range (high – cycle fatigue) on a plot of cyclic stress(S) level
versus number of cycles to failure (N). Shown in Figure 2.44 is a typical S-N curve for aluminium.

Figure 2.35 : Typical S-N curve for Aluminium [Ben P Allen]

Constant amplitude S-N curves are usually plotted in semi-log or log-log coordinate scales. They carry important design information and are still used in engineering practise to estimate long lives of machine parts. To estimate the life data for high load levels of machine parts for high load levels where plasticity effects become important (i.e., for short lives or low-cycle fatigue), strain-life relationships are more appropriate.

The transition between low and high-cycle fatigue usually occurs between $10^3$ and $10^5$ cycles [Sobczyk and Spencer, Jr., 1992]. The S-N relationship is determined for a specified value of $\sigma_m$, $R(R = \sigma_{\min} / \sigma_{\max})$ or $A(A = \sigma_u / \sigma_m)$. Most determinations of the fatigue properties of materials have been made in complete reversed bending, where the
mean stress is zero. It will be noted that this S-N curve is concerned chiefly with fatigue failure at high numbers of cycles \( N > 10^5 \) cycles. Under these conditions the stress, on a gross scale, is elastic, but as we shall see shortly the metal deforms plastically in a highly localized way. At higher stresses the fatigue life is progressively decreased, but the gross plastic deformation makes interpretation difficult in terms of stress. For the low-cycle fatigue region \( N < 10^6 \) or \( 10^7 \) cycles tests are conducted with controlled cycles of elastic plus plastic strain instead of controlled load or stress cycles.

The usual procedure for determining an S-N curve is to test the first specimen at a high stress where failure is expected in a fairly short number of cycles, for example at about two-thirds the static tensile strength of the material. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified number of cycles, which is usually at least \( 10^7 \) cycles. The highest stress at which the runout (non-failure) is obtained is taken as the fatigue limit. For materials without a fatigue limit the test is usually terminated for practical considerations at a low stress where the life is about \( 10^8 \) or \( 5 \times 10^8 \) cycles. The S-N curve is usually determined with about 8 to 12 specimens [Sobczyk and Spencer, Jr., 1992].

### 2.5.3. Scatter in fatigue data

Experimental data obtained from testing specimens under various loading conditions constitute the main source of information about
fatigue of engineering materials. However these data, regardless of how carefully they are generated, show significant random scatter that may conceal their informational content. Scatter in fatigue test data is therefore a very significant issue in the analysis of the fatigue phenomenon and in prediction of fatigue reliability of engineering structures. Three sources of variability in experimentally obtained fatigue data are commonly regarded as the most decisive, namely:

• The difference in material behaviour among identically prepared specimens (due to difference in stress concentration at grain boundaries, effects of thermal processing, etc);

• Uncertainty in the fatigue and fracture process itself; and,

• The difference in environment among tests at the same load conditions and with the same material.

Usually it is not easy to separate these sources of uncertainty in a quantitative manner. In traditional fatigue tests, the applied stress is usually fixed and treated as an independent variable, and the number of cycles to failure, \( N \), is determined for each specimen. The scatter of fatigue life at a prescribed stress level is then quantified in a relation between the number of cycles and the proportion of failed specimens (prior to \( N \) cycles). Along this line Sinclair and Dolan performed an extensive fatigue study involving 174 identical highly polished unnotched 7075-T6 aluminium alloy specimens using six different stress levels. The results are shown in the figure below and show significant scatter in
fatigue life. This and other investigations also indicate that greater scatter usually occurs at the higher levels.

This can be attributed to the greater percentage of life needed at lower stress levels to initiate small micro-cracks and then to propagate macro-cracks. If the fatigue process is characterized by the growth of a dominant crack, then the data on crack length versus the number of cycles should be gathered and analysed.

### 2.5.4. Fractography

Fractography is a part of materials science that involves describing the topography of a separation surface formed during a breakage of the material continuity. Descriptions of the characteristic features of fracture surface and their classification are very important for establishing the dependence between decohesion mechanism (dependent on physical and mechanical properties) and material microstructure (determined by chemical composition and production technology).

Fractographic examination of metals is used in metal science to:

- Evaluate the cause of material destruction by revealing and identifying discontinuities such as internal cracks, porosity, inclusions, and chemical or microstructural inhomogeneities;
- Determine the decohesion mechanism by describing and classifying the characteristic morphological features of the fracture surface;
• Estimate the stress field acting during decohesion by analysing fracture morphology, taking into account both fracture surfaces;
• Identify crack paths.

2.5.4.1. Morphology of Ductile Fracture

Features of the ductile fracture surface include:

• Voids that are concave micro-regions of the initiation of the material decohesion, usually around the hard dispersed particles or other matrix discontinuities;
• Dimples that are rounded hollows on the fracture surface. The shape and size of the dimples are determined by the size and the distribution of the microstructure discontinuities (micropores, disperse particles that become microcracks), plastic properties of the material, and the acting stresses. The dimples of different morphology can exist simultaneously on the surface of the ductile fracture, depending on the active local stress and strain states.
• Tear dimples, open or closed, form under complex stress state (e.g., tensile and bending or torsion). Round ends of the open tear dimples appear opposite the crack initiation region and are the same on both fracture surfaces.
• Shear dimples present in the shear areas of the plastically deformed material and are the oval hollows on the neck shear surface, in the region of the plain stress state. Oval shear dimples formed during shear of the material can be open or closed. They
are elongated into direction of the stress effect, and their coalescence takes place on the plane of the maximum shear stress.

2.5.4.2. Fatigue Fracture

Fatigue fractures belong to a particular group of fractures from the viewpoint of the formation mechanism, the material decohesion and the specific Morphology of the surface. Fatigue fracture can be classified according to the following criteria:

- The type of loading;
- The range of the Wohler’s curve.

According to the first criterion, the fractures can be defined as typical fatigue fractures of fatigue fractures caused by:

- Thermal fatigue;
- Corrosion;
- Repeated fatigue loading;
- Repeated loading of ultrasonic frequency;

According to the second criterion, the following classification can be defined:

- Fatigue fracture in the range of the short time and limited fatigue resistance;
- Fatigue fracture in the range of the loading of the fatigue limit (characterized by presence of the plastic deformation).
2.5.4.3. Morphology of Fatigue Fracture

The characteristic features of fatigue fractures are fatigue striations and the indent traces. Fatigue striations are elongated bands of material alternately concave and convex, parallel to the crack propagation direction. In aluminium alloys, they are more continuous and regular than in steels. Brittle and plastic striations can be observed on fatigue fracture surfaces. The brittle striations are crossed with perpendicular steps. The line of each step is parallel to the crack propagation direction. They are often present in dispersion-hardened aluminium alloys. In the macroscopic scale, fatigue lines are also visible on the fatigue fracture surface. The distribution and spacing of the fatigue striations reflect the changes in the rate of the main crack propagation. Each fatigue line is composed of thousands of fatigue striations, so it represents several cycles of loading.

2.6. MICROHARDNESS TESTING

In engineering, hardness is most commonly defined as the resistance of a material to indentation. Indentation is the pressing of a hard round ball or point against the material sample with a known force so that a depression is made. The depression or indentation results from plastic deformation beneath the indenter. Some specific characteristics of the indentation such as its size or depth, is then taken as a measure of hardness. Vickers differs from other hardness tests in that a diamond-shaped indenter is used. The indenter is a diamond pyramid with a square base. The angle between the facets of the pyramid is \( \alpha = 136^\circ \).
This shape results in the depth of penetration, \( h \), being one-seventh of the indentation size, \( d \), measured on the diagonal of the Vickers hardness number \( HV \), is obtained by dividing the applied force \( P \) by the surface area of the pyramidal expression.

This yields:

\[
HV = \frac{2P}{d^2} \sin \frac{\alpha}{2}
\]

where \( d \) is in millimetres and \( P \) in kilograms. The standard pyramidal shape causes the indentation to be geometrically similar regardless of its size. For reasons based on plasticity theory, this geometric similarity is expected to result in the Vickers hardness value being independent of the magnitude of the force used.

Hence a wide variety of standard forces, usually between 1kg and 120kg, are used so that essentially all solid materials can be included in a single wide-ranging hardness scale. Vickers microhardness testing was performed using the testing machine shown in Figure 2.44. The sample used in the test was first mounted and then polished.
2.6. SUMMARY

The literature review in this chapter covers Friction Stir Welding, MIG-Laser Hybrid Welding, Tool design, fatigue and Microhardness testing. In Friction Stir Welding the process parameters that are important and need to be considered when performing a FSW weld are explained. These include the dwell time, the plunge depth and welding speeds. All these are influential on the final weld quality of the weld. Microstructural classification of the welds obtained from the FSW process is explained as they form the basis of analysis when analysing the results.

In MIG-Laser hybrid welding the process parameters vital in the process are explained. These include processing speeds, the shielding gas type used in the process and sample preparation. The influence of having gaps between the plates being welded, the welding speed, weld penetration and weld quality are explained in detail, and relevant
examples discussed. The weld quality is directly related to the weld penetration and speeds used during the welding processes. The two welding processes are complex individually. Industrial applications of the MIG-Laser hybrid welding are given.

In tool design the steps that lead to a meaningful design are explained together with all that was considered when designing the tool for Friction Stir Processing. The FSP tool concept discussed in 2.4.4 would be used to carry out friction stir processing of aluminium alloy plates. The concept of fatigue and fatigue testing are explained together with factors affecting fatigue. Microhardness testing is the last section discussed which forms part of mechanical testing. Chapter 3 discusses steps taken in evaluating the tool designed.
CHAPTER 3

TOOL DESIGN TRIALS

3.1. INTRODUCTION

This chapter explains all the steps that lead to finalising the Friction Stir Processing process of the MIG-Laser hybrid welded plates. This includes tool design trials where it was determined whether the designed tool would be able to do what it was designed for. All the observations from the tool design trials are explained followed by the weld parameter trials where the nominal speeds for FSP with the designed tool were determined. Tensile testing was performed on the welded plates and even though the study was not intensive the aim was to obtain the best parameter setup for the Friction Stir Processing tool.

3.2. TOOL DESIGN TRIALS

3.2.1. Trial Number 1

Figure 3.1 shows the testing of the FSP tool. The bead on the 6082-T6 AA plates was welded with arc welding using a filler material to simulate the root resulting from the MLH welding process. The welding direction in Figure 3.1 and the filler material being displaced can be seen. Figure 3.2 shows the side flash formed as a result of Friction Stir Processing using the FSP concept tool. Weld runs were done with the new tool to evaluate the possibility of root dressing MIG-Laser Hybrid welded joints.
A filler material for welding aluminium was used to weld the two plates together. This was done to simulate the root profile found on MIG-Laser Hybrid welded aluminium alloy plates. The filler material was stirred under high temperatures and displaced to the sides of the welded plates as shown in Figures 3.1 and 3.2. The tool managed to overcome the root bead but there were large amounts of side flash on the welded joint due to the filler material being displaced by the tool. The welding parameters used are shown in Table 3.1:

Table 3.1: Welding parameters for trial weld number 1

<table>
<thead>
<tr>
<th>Tilt Angle (Degrees)</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>400</td>
<td>100</td>
</tr>
</tbody>
</table>
3.2.2. Trial Number 2

Figure 3.3 shows another set of plates welded with a filler material and machined on the milling machine to simulate the root found on MLH welded joints.

![Simulated root bead](image)

Figure 3.3: Trial number 2 with the new FSP tool

The two plates were welded together by arc welding to produce a similar profile to the root bead found in MIG-Laser hybrid welded plates. The resulting root bead was then machined on the sides to form a rectangular shape simulating the root bead and, after Friction Stir Processing was performed, there was no side flash. The tool managed to produce a visually acceptable weld. The welding parameters are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Tilt Angle (Degrees)</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>400</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.2: Welding parameters for trial weld number 2
3.2.3. Trial Number 3

Figure 3.4 shows the FSP tool used on the MLH welded plates and the root bead being deposited on one side as side flash. Figure 3.54 shows the keyhole and the weld which are typical features of the FSP process.

Figure 3.4: Trial number 3 with the new FSP tool on MLH welded plate

Figure 3.5: Trial Friction Stir Processed aluminium alloy plate

A third weld run was done on a MIG-Laser Hybrid welded plate and compared with other weld trial runs, the material was mixed back into the FSW joint. The high temperatures (520°C) enabled the tool to move with ease and the amount of side flash was minimal as it was formed as a
result of the excess root material that was originally there before the FSP process. Another important observation was that, compared to the other weld trials with MLH welded plate, it was a lot easier for the weld root material to be stirred back with the parent plate material. The welding parameters are shown in Table 3.3.

<table>
<thead>
<tr>
<th>Tilt Angle (Degrees)</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>400</td>
<td>100</td>
</tr>
</tbody>
</table>

### 3.2.4. Trial Number 4

Figure 3.6 shows the original FSW tool being used to weld two 6mm 6082-T6AA plates. The plates were to be used for comparison purposes and also to compare the influence of the change in welding speeds.

A fourth trial weld was performed with the FSW tool to determine the effect of change in welding speeds from 400rpm and 100mm/min to 500 rpm and 80mm/min in welding 6mm thick 6082-T6 aluminium alloy. The tilt angle remained the same but the spindle speed was increased to 500rpm and the feed rate reduced to 80mm/min. Tensile specimens were
cut from the welded plates and then machined on the CNC milling machine in preparation for tensile testing.

Table 3.4: Welding parameters for trial weld number 3

<table>
<thead>
<tr>
<th>Tilt Angle (Degrees)</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>500</td>
<td>80</td>
</tr>
</tbody>
</table>

The results show the importance of welding speeds in the FSW process. Therefore, for research purposes, it is critical to achieve the optimum parameter settings for the material being used.

3.2.5. Performance Evaluation

The tool concept proved to work in its intended purpose, performing root dressing on MIG-Laser hybrid welded aluminium alloy plates. The tool was able to displace the root /bead material and mix it back with the parent plate, while excess material came out as side flash. The tool exit hole was examined and its appearance gave an indication of the weld quality. According to Lloyd’s register with a good weld, the circle around the hole has to be 100% complete and as the quality degrades the circle becomes less than 100%. The circle is also an indication of a correct plunge depth.

3.2.6. Tensile Testing

Figure 3.7 shows tensile samples taken from the Friction Stir Processed plate. As can be seen on the picture the samples have weld surface characteristics of the two processes namely FSP and MLH processes.
Mechanical testing in the form of tensile testing was performed on the FSP plates and the **Instron 8801** servo-hydraulic machine used for testing the samples. The FSP samples had a better tensile strength than MLH welded samples and the elongation was twice that obtained when testing MLH welded samples. All the samples failed in the HAZ as a result of the combination of the two processes; the weld surface finish was comparable with that obtained in Friction Stir Welding. The failure of the tensile sample initiated from the MLH welded portion and the reason for this failure could have been the refined grain structure brought about by the FSP process. Although the results obtained in this exercise were good they could not be considered vital, as other factors crucial in FSP were not attained.

The aim of this trial was to determine the possibility of performing FSP on MLH welded plates. Attention was not paid to the welding speeds and the stability temperature region.
Table 3.5: Trial results

<table>
<thead>
<tr>
<th></th>
<th>FSW</th>
<th>MLH</th>
<th>FSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>226MPa</td>
<td>220.8MPa</td>
<td>222MPa</td>
</tr>
<tr>
<td>YS</td>
<td>120MPa</td>
<td>150MPa</td>
<td>160MPa</td>
</tr>
</tbody>
</table>

These trial results gave an indication that FSP had a positive influence on the welded joints with regard to tensile strength. MLH welded aluminium plates are known for their brittle joints. The FSP process increased ductility and reduced brittleness of the welded joints.

The results were an indication that FSP could have a positive influence on MLH welded plates. The most noticeable improvement with the change in welding speeds was the location of the fracture surface which, in the case of higher speeds, was on the retreating side outside the welded area in the heat-affected zone. Welds done at lower welding speeds failed on the retreating side at the border of the weld area and the parent material, and it was apparent that at lower speeds the heat affected zone is smaller. The change in speeds resulted in an increase in the ultimate tensile strength (UTS) to 226MPa. Welds done at 400rpm and 100mm/min gave an average UTS of 209MPa. It could be concluded from these results that by increasing the welding speeds there is an increase in size of the HAZ area. This statement is in agreement with what was discovered by Yan and Reynolds (Section 2.2.1).
Results show the importance of welding speeds in the FSW process. Therefore for research purposes it is critical to get optimum parameter settings for the material being used.

3.3. FSP PARAMETER TRIALS

Determining the Optimum Speeds for FS Processing

Compared to the Friction Stir Welding (FSW) process, which has established process parameters for each grade of aluminium alloy, Friction Stir Processing (FSP) lags behind. FSP is performed mostly on already welded aluminium plates or parent plates to introduce superplasticity properties so it becomes difficult to standardise the process parameters; the other reason is that the plunge depth as well as the area to be processed depends entirely on the design of the tool. There are no set standards for FSP tool design.

The FSP process is an adaptation of the FSW process. Most of the rules applying to FSW also apply to FSP. It has been proven that the shoulder of a tool generates the most heat with the probe involved in the mixing of the material beneath the shoulder; it follows that the bigger the tool shoulder, the higher will be the resulting heat input and vice versa. This is in agreement with proof that each FSP tool design will always have its own optimum operating welding speeds. As there are no standard set speeds for FSP, trial welds were carried out to determine the best speeds suitable for FSP concept tool as shown in Figure 3.3.
3.3.1. Weld 1 [600rpm: 80mm/min: 0.4mm; 150mm]

Figure 3.8 shows the appearance of a keyhole, the surface welded at 600rpm and a feed rate of 80mm/min. Figure 3.9 shows the structure through the cross section of weld 1. In this block 600rpm is the rotational speed of the welding tool, 80mm/min being the movement of the bed, 0.4mm being the plunge depth and 150mm the length welded.

![Figure 3.8: Keyhole for weld 1](image)

![Figure 3.9: Macrostructure of weld 1](image)

The welding speeds used for this weld generated a lot of side flash around the welded area. The welding speed used resulted in an uneven surface finish at the start of the weld. An improvement was found after about 50mm from the start of the weld. The surface looked flaky and there was no consistency in appearance. The plunge depth was adequate as was the ratio between the spindle and the welding speed while the nugget region was wider compared to the lower rotational speeds tested in these weld trials.
3.3.2. **Weld 2**

[600rpm: 100mm/min: 0.4mm; 150mm]

Figure 3.10 shows the weld surface appearance formed as a result of a change in welding speeds. Figure 3.11 shows the structure through the cross section formed as a result of the speed used.

![Figure 3.10: Welded surface and the keyhole for weld](image)

![Figure 3.11: Macrostructure for weld 2](image)

The top surface looked worse in appearance when compared to that of weld number 1 and the amount of side flash formed for this weld was negligible. At times it seemed as if the tool was not touching the surface and the heat generated was insufficient. From observations it looked like the welded material could be consolidated and the welded surface had a consistent surface finish. When compared to standard Friction Stir Welding exit holes the one found at weld 2 differed by about 10% and
the onion rings could be clearly distinguished on the cross sectional area.

3.3.3. Weld 3

[600rpm: 120mm/min: 0.4mm; 150mm]

Figure 3.12 shows the weld surface appearance resulting from the welding speeds used, namely 600rpm and 120mm/min. Figure 3.13 shows the macrostructure resulting from the speeds used.

The weld surface finish beneath the tool shoulder of weld 3 was not acceptable and the side flash found at the exit hole was also unacceptable. Too much heat was generated and thinning of the plates could have occurred as the material was displaced and deposited as side flash. It seem as if there was no balance between the welding
speed and the spindle speed. It could be that the spindle speed was too high for the welding speed used.

The other observation from weld 3 was the inconsistency on the weld surface. The weld surface formed beneath the shoulder started with a flaky surface but stabilised after 50mm from the start. For a weld to be accepted it had to be uniform from the start to the end.

### 3.3.4. Weld 4 [550rpm: 120mm/min: 0.4mm; 150mm]

Figure 3.14 shows the surface appearance resulting from speeds of 550rpm and 120mm/min used during the welding process. Figure 3.15 shows the cross-sectional structure resulting from the speeds used.

![Figure 3.14: Weld 4 keyhole](image1)

![Figure 3.15: Weld 4 macrostructure](image2)
Weld 4 had a good weld surface formed beneath the tool shoulder but the advancing and retreating sides did not have the same tool shoulder footprint. The advancing side was a lot rougher compared with the smooth surface exhibited by the retreating side. The exit hole did not exhibit equivalent flash distributed on the periphery as required by FSW weld standards. The nugget region had a tendency to reduce in size as the rotational speed was reduced.

3.3.5. Weld 5  

[500rpm: 120mm/min: 0.4mm; 150mm]

Figure 3.16 shows the surface appearance resulting from speeds of 500rpm and 120mm/min used during the welding process. Figure 3.17 shows the cross sectional structure resulting from the speeds used.

![Figure 3.16: Weld 5 keyhole](image)

![Figure 3.17: Weld 5 macrostructure](image)
Weld 5 started off with an inconsistent weld surface formed beneath the tool shoulder for the first 30mm thereafter the weld surface formed beneath the shoulder and maintained its structure. The exit keyhole was similar to the one found at weld 6 but it had about 15% more flash on the exit hole. The side flash found at this weld was more pronounced compared to weld 6, and, incidentally this was one of the best welds when reviewing the tensile results.

3.3.6. **Weld 6**  
[450rpm: 120mm/min: 0.4mm; 150mm]

Figure 3.18 shows the weld surface appearance formed as a result of a reduction in rotational speeds from 500rpm to 450rpm, and Figure 3.19 shows the resulting cross sectional structure.

![Figure 3.18: Weld 6 keyhole](image)

Weld 6 started off with what could happen with a longer dwell time period when resulting excess material at the start of the weld and the
surface improved and stayed constant for the duration of the weld. The weld surface formed beneath the tool shoulder in weld 6 was acceptable and comparable to standards available in the Lloyd’s Register Weld Quality Requirements. The amount of side flash was minimal and the tool shoulder footprint was the same on the retreating side as on the advancing side. There was a close balance between welding speed and rotational speed and consistency in the welded area from the beginning to the end of the weld.

3.3.7 Weld 7 [400rpm: 120mm/min: 0.4mm; 150mm]

Figure 3.20 shows a weld surface appearance and Figure 3.21 the cross sectional structure resulting from the welding speeds used. The weld shows a typical FSP tool footprint and side flash dependent on the weld parameters used.

![Figure 3.20: Weld 7 keyhole](image)

![Figure 3.21: Weld 7 Macrostructure](image)
The weld surface formed beneath the shoulder had a good surface finish but a lot of side flash was caused by high temperatures. According to Krishnan et al [2001] very high temperatures would also reduce friction and the weld was likely to contain a lot of flash.

The amount of side flash that was deposited around the exit hole was not of an acceptable standard and the microstructure of the weld showed no signs of voids when compared to weld 8 (same weld parameters except for the plunge depth). A weld like this one looks unacceptable and there would be a need to skim the surface after every weld made under the same welding parameters. Even though the surface found between the retreating and advancing sides looked acceptable, the amount of side flash was excessive and the exit hole resembled that of Friction Stir Spot Welding (FSSW).

### 3.3.8. Weld 8  
**[400rpm: 120mm/min: 0.3mm; 150mm]**

Figure 3.22 shows a weld surface appearance resulting from speeds used (400rpm, 120mm/min), which look different when compared to others evaluated in this chapter. Figure 3.23 shows the weld cross sectional structure resulting from the weld parameters used.
The weld surface formed beneath the shoulder had the roughest finish of all the welds evaluated, due to the fact that the plunge depth was formed on this weld and it could be seen that insufficient plunge caused the formation of sub-surface voids. Enough heat could have been generated but with the lack of axial force the material could not be stirred sufficiently. The nugget area was not clearly defined in this weld and onion ring-like formations could be observed towards the right side of the void.
The presence of the void clearly illustrated the importance of having the correct plunge in depth and in this exercise its importance had been proved. The exercise showed the complexity of the FSW process, in that one could have a good balance of rotational and welding speeds. Without a correct plunge depth the weld would be very weak due to the presence of sub-surface voids. Failure in a weld normally starts where there is a void. Tensile results clearly reveal that this was the weakest weld as it had the lowest ultimate tensile strength (UTS).

Table 3.6: Welding speeds, Plunge Depth and Tensile results

<table>
<thead>
<tr>
<th>WELD</th>
<th>Rotational Speed (rpm)</th>
<th>Welding Speed (mm/min)</th>
<th>Plunge Depth (mm)</th>
<th>Tensile Strength (MPa)</th>
<th>0.2% Proof Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>600</td>
<td>80</td>
<td>0.4</td>
<td>111.7</td>
<td>76.3</td>
</tr>
<tr>
<td>1B</td>
<td>600</td>
<td>80</td>
<td>0.4</td>
<td>122.0</td>
<td>84.3</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>116.9</strong></td>
<td><strong>80.3</strong></td>
</tr>
<tr>
<td>2A</td>
<td>600</td>
<td>100</td>
<td>0.4</td>
<td>126.9</td>
<td>80.5</td>
</tr>
<tr>
<td>2B</td>
<td>600</td>
<td>100</td>
<td>0.4</td>
<td>122.4</td>
<td>80.6</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>124.7</strong></td>
<td><strong>80.5</strong></td>
</tr>
<tr>
<td>3A</td>
<td>600</td>
<td>120</td>
<td>0.4</td>
<td>121.4</td>
<td>82.0</td>
</tr>
<tr>
<td>3B</td>
<td>600</td>
<td>120</td>
<td>0.4</td>
<td>127.5</td>
<td>87.3</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>124.5</strong></td>
<td><strong>84.7</strong></td>
</tr>
<tr>
<td>4A</td>
<td>600</td>
<td>120</td>
<td>0.4</td>
<td>133.4</td>
<td>81.7</td>
</tr>
<tr>
<td>4B</td>
<td>600</td>
<td>120</td>
<td>0.4</td>
<td>138.8</td>
<td>86.1</td>
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<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>136.1</strong></td>
<td><strong>83.4</strong></td>
</tr>
<tr>
<td>5A</td>
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<td>120</td>
<td>0.4</td>
<td>132.3</td>
<td>83.6</td>
</tr>
<tr>
<td>5B</td>
<td>600</td>
<td>120</td>
<td>0.4</td>
<td>129.7</td>
<td>82.3</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>131.0</strong></td>
<td><strong>83.0</strong></td>
</tr>
<tr>
<td>6A</td>
<td>450</td>
<td>120</td>
<td>0.4</td>
<td>126.5</td>
<td>83.5</td>
</tr>
<tr>
<td>6B</td>
<td>450</td>
<td>120</td>
<td>0.4</td>
<td>128.3</td>
<td>83.5</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>127.4</strong></td>
<td><strong>83.5</strong></td>
</tr>
<tr>
<td>7A</td>
<td>400</td>
<td>120</td>
<td>0.4</td>
<td>123.2</td>
<td>81.5</td>
</tr>
<tr>
<td>7B</td>
<td>400</td>
<td>120</td>
<td>0.4</td>
<td>118.4</td>
<td>79.5</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>120.8</strong></td>
<td><strong>80.5</strong></td>
</tr>
<tr>
<td>8A</td>
<td>400</td>
<td>120</td>
<td>0.3</td>
<td>74.8</td>
<td>46.0</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>74.8</strong></td>
<td><strong>45</strong></td>
</tr>
</tbody>
</table>
In Table 3.6 all the welding speeds and UTS values have been tabulated together with the plunge depth used. The results obtained clearly show the influence welding speeds and the plunge depth have on the Ultimate Tensile Strength of the weld. Results obtained in this exercise are for the tool geometry of the FSP tool, and, if there was another tool different in design, it would have to undergo the same trials. From the results it is also clear that there is room for improvement of the tool. A graphical representation of the results showing a stress versus extension graph is given in Appendix C.

3.4. SUMMARY

This chapter deals with the evaluation of the tool design for Friction Stir Processing of MLH joint. The tool design was first evaluated in welds similar to those found in MLH joints to see if it would be able to do what it was designed for. Dummy plates welded had beads to simulate the weld bead formed as a result of the MIG-Laser hybrid Welding process.

As is the norm with FSW and FSP processes any new tool design has to be tested and optimum operating conditions determined for the designed FSP tool. Varying rotational and welding speeds were used to determine their influence on the final ultimate tensile strength of the weld. The effect of plunge depth was also investigated. The weld specification data (Lloyd's Register of shipping) sheet was used to check and determine whether the quality of the welds was acceptable.
CHAPTER 4

EXPERIMENTAL SETUP

4.1. INTRODUCTION

The steps that lead to producing a friction stir weld and a friction stir processed weld will be explained in this chapter. Processes like plate preparation which include milling and drilling and the tool used are described. The experimental setup for the following procedures is described: FSP; FSW; MLH; temperature profiles and mechanical testing. The guidelines in the form of a tables list how the MLH, FSW and FSP processes were carried out and all the parameters used in these processes.

4.2. THE FSW MACHINE

Figure 4.1 shows the FSW machine used in the research which has a capability of welding varying plate thicknesses with ease. Flat aluminium and copper plates with a thickness of 1.6mm to a thickness of 8mm have been welded on the machine. Cylindrical aluminium plates have also been welded with a specially designed clamping and drive system to work with the FSW machine.
Figure 4.1: The FSW machine

Plates were welded using a converted Correa Milling machine with PLC/PC control and data acquisition system. According to Blignault et al 2003, the minimum requirements that need to be considered when purchasing a milling machine with the intention of transforming it into a Friction Stir Welding machine are:

- Sufficient power to generate constant torque at various spindle speeds;
- High Z-force capability (at least 1.5 tons depending on material thickness);
- Vertical spindle rotation;
- Fairly big feed-bed for welding big sheet metal alloys;
- Stable machine with rigid bed that can handle heavy vibration;
- Spindle head (quill) that can tilt to the preferred angle of $0 - 5^\circ$;
- Wide variety of feed and spindle speeds ratios;
- Preferably a second Z-axis that can be controlled individually during the weld.
The system is controlled with two motors only, namely spindle motor and feed motor. These motors are linked to drive controllers with RS 485 connection that make interface possible with a PC. Feedback for positioning purposes is given by means of optical encoders providing pulses related to linear movement. The spindle motor is rated at 5.5kW and the feed bed motor is rated at 1.5kW. Both these motors use mechanical gearboxes to increase the torque on the output shaft. The main spindle motor provides the spindle rotation while the feed bed motor supplies power to all the three axis movements of the bed. The various axes of the bed namely X, Y and Z are engaged with 24V electromagnetic clutches. The clutches are in turn controlled by contactors that are linked to the PC with digital I/O boards. Limit switches and emergency stop buttons are also linked to the PC with the PCI boards.

4.3. MATERIAL CHARACTERISTICS

The material used in the study was 6082-T6 aluminium alloy with a thickness of 6mm which belongs to the group of Al-Mg-Si alloys. This material is heat-treatable which means that mechanical properties may be improved by the solution heat-treatment process. Al-Mg-Si alloys are widely used as medium strength structural alloys which have additional advantages of good weldability, corrosion resistance, and immunity to stress-corrosion cracking. Just as the 5xxx series of alloys comprise the bulk sheet products, the 6xxx series are used for the majority of extrusions, the smaller quantities being available as sheet and plate.
Magnesium and silicon are added either in balanced amounts to form quasi-binary $\text{Al-Mg-Si}$ alloys ($\text{Mg:Si} \approx 1.73:1$), or with an excess of silicon above that needed to form $\text{Mg-Si}$. $\text{Al-Mg-Si}$ alloys are normally aged at approximately 170°C. During the commercial processing, there may be a delay at room temperature between quenching and artificial ageing which may modify the mechanical properties that are developed [Polmear et al, 1981].

Compared to heat treatable alloys the increased strength is obtained with little sacrifice in ductility. Heat treatable alloys have the further advantage that they can be re-heat treated after annealing to restore the original properties. With these alloys, which are aged immediately after quenching, it has a consequent adverse effect on tensile properties. The reverse occurs in alloys containing less than 0.9% $\text{Mg-Si}$. The addition of 0.25% copper lessens effects of delays at room temperature because copper reduces the rate of natural ageing in Al-Mg-Si alloys. As with the 2xxx series, there is an $\text{Al-Mg-Si}$ alloy (6262) containing additions of lead and bismuth to improve machining characteristics.

Although the machinability of this alloy is below that of Al-Cu alloy 2011, it is not susceptible to stress-corrosion cracking and is preferred for more highly stressed fittings [Polmear et al 1981]. The typical chemical composition for 6082-T6 is given in Table 4.1.
Table 4.1: Chemical composition of 6082-T6

<table>
<thead>
<tr>
<th>Component</th>
<th>Al</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>95.2 - 98.3</td>
<td>Max 0.25</td>
<td>Max 0.1</td>
<td>Max 0.5</td>
<td>0.6 - 1.2</td>
</tr>
</tbody>
</table>

Table 4.2: Chemical composition of 4043 filler material

<table>
<thead>
<tr>
<th>Component</th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>Be</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>99.85</td>
<td>45 - 60</td>
<td>0.8</td>
<td>0.3</td>
<td>0.0008</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The T designates solution heat treatment of heat-treatable alloys and T6 means the plates have been solution heat-treated, quenched and artificially aged to achieve highest strength. Shown in Table 4.2 is the chemical composition of the filler material used when welding with the MIG-Laser Hybrid process. The main alloying element is silicon, which has a maximum of 6% in the chemical composition. One of the characteristic features of the filler material used are the following: low ductility; lower tensile strength and less prone to porosity.

4.4. PLATE PREPARATION

4.4.1. Milling

Plates of 6082-T6 aluminium alloy were received as strips of $800 \times 40 \times 6$ mm which were then cut into strips of $400 \times 40 \times 6$ mm. This was done to accommodate the plates on the FSW clamping system and avoid bending that normally occurs at the middle of the plate during
welding. A maximum of 13 plates (depending on the diameter of the slub cutter used) were machined on the milling machine to make them parallel. G-clamps were used to hold the plates firmly together when the unmachined side had to be machined. The aim for machining both sides of the plates was to make them parallel for the FSW machine clamping system and also for gaps to be welded between the plates. The parallel plates enabled uniformity when gaps had to be welded between the plates and the machined plates proved useful and easy to work with during the welding process. A blind hole jig was used and all the plates that were machined on the milling machine were drilled in three points, ensuring consistency in the whole plate preparation. All the sharp edges formed as a result of milling were removed.

4.4.2. Drilling

Two special jigs were made to aid in the marking of spots on the milled plates in preparation for the drilling operation process, and thereafter plates were ready for welding on the FSW machine. Three blind holes were drilled on each strip of plate to accommodate the cap screws of the clamping system. The cap screws were tightened using a torque wrench to the same torque level which minimised the movement of the aluminium alloy plates during the welding process. During the FSW process high forces are generated by the tool as it plunges onto the work pieces to be welded. Once the tool has plunged into the work pieces the plates have a tendency to drift apart. The movement of the plates became more evident when gaps had to be welded between the plates.
but with the 0mm gap the plates had no opportunity to move. Figure 4.2 shows a typical clamp setup for the FSW machine.

Figure 4.2: Clamping Operation

4.5. TOOL

The FSW and FSP tool steel H13 (W302) was obtained from Bohler Steels SA and the tools were then heat-treated to approximately $R_c \approx 54$ after machining. The tool pin accommodates a 0.5mm diameter thermocouple probe and the 0.7mm diameter hole inside the tool was made via electron discharge machining. A diagram showing dimensions for the FSW tool designed by Dr Calvin Blignault, and the FSP tool concept are given in Appendix A.

4.6. WELDING PROCEDURE

4.6.1 Welds 1 - 15 - Friction Stir Welded Specimens

Table 4.3 indicates the major parameters used in the welding of FSW samples for all the gaps. The FSW tool designed by Dr Calvin Blignault was used to weld all the plates and the dwell time was maintained at 8
seconds for all the gaps. The way in which the samples were obtained is also indicated in the table.

Table 4.3: Weld matrix for FSW

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Gap (mm)</th>
<th>Rotational Speed (rpm)</th>
<th>Welding Speed (mm/min)</th>
<th>Tensile Samples</th>
<th>Fatigue Samples</th>
<th>Microstructure Samples</th>
<th>Microhardness Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09</td>
<td>0</td>
<td>500</td>
<td>80</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.10</td>
<td>0.5</td>
<td>500</td>
<td>80</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.11</td>
<td>1</td>
<td>500</td>
<td>80</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.12</td>
<td>0</td>
<td>500</td>
<td>80</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.13</td>
<td>0.5</td>
<td>500</td>
<td>80</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.14</td>
<td>1</td>
<td>500</td>
<td>80</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The welded plates were used to compare FSW to MLH and FSP welding processes. The same table shows partly the welding matrix developed for the FSW process with all the process parameters used during the FSW procedure. The gaps between the plates were obtained with the aid of feeler gauges and the backing plate used as a reference point as it has a marked line showing the centerline of the backing plate, which also corresponds to the pathway of the welding tool. For 1mm gaps the rear plate was fixed at the centre and the front plate offset by 0.5mm and then clamped tightly onto the backing plate.

The rear plate was then offset by 1mm with the feeler gauge resulting in a 1mm gap between the plates. The same procedure was applied for the 0.5mm gap. Figure 4.3 shows the FSW process in progress using the tool designed by Dr Calvin Blignault.
The speeds of 500rpm and 80mm/min were determined at TWI and they were found to be the suitable settings for 6082-T6 aluminium alloy. Preliminary testing on 500rpm and 80mm/min feedrate gave higher tensile strength values than welding speeds of 400rpm and 120mm/min previously used for the welding procedure. This observation underlined the importance of welding speeds in the FSW process. Samples for mechanical and metallurgical testing were welded using the predetermined welding speeds for the 6082-T6 aluminium alloy. The FSW process needed no special surface preparation or consumables before welding can proceed.

Adjustments for the FSW process were made only to the welding speed, feed rate and the tilt angle. The 6082-T6 welded plates are characterized by a good surface finish which is a result of the alloying elements used in the manufacture of this alloy. The FSW process requires a strong clamping system as the lateral forces developed during this process tend to drift the plates apart during the plunge-in period and when welding.
The current clamping system available on the FSW machine is able to hold the plates firmly during the welding process and the cap screws and bolts used have to be replaced once in a while as they get worn over time, and lose their grip and effectiveness. The effect of lateral forces developed during the FSW process became evident with the introduction of gaps. When welding the 0mm gap excess material from the weld was deposited as side flash but with a gap of 0.5mm or 1mm gap excess material filled the gap space between the plates and there was a reduction in the amount of side flash developed.

Another observation was the change in the gap width during the welding process which was a result of the heat generated during the FSW process. For example, before welding a gap of 0.5mm, it was ensured that the gap remained constant from one end to the other end but after the welding process no space could be found between the welded plates. All the welds were started at about 30mm from the beginning of the plate and completed when a distance of 20mm remained from the far end and due to the heat generated by the welding process the gaps closed up.

4.6.2 Welds 16 - 18 - MIG-Laser Hybrid Welded Specimens

Table 4.4 shows the matrix used to weld all the gaps for the MLH welding process. The matrix acted as a guide for selecting the samples and grouping them for mechanical testing. It also shows that welding
speeds for the MLH process are at least more than 20 times faster than both FSW and FSP processes.

Table 4.4: Weld matrix for MLH

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Gap (mm)</th>
<th>Welding Speed (mm/min)</th>
<th>Tensile Samples</th>
<th>Fatigue Samples</th>
<th>Microstructure Samples</th>
<th>Microhardness Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>2000</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>0.5</td>
<td>2000</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>1500</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

When a filler material is used during the MLH process the weld deposit alloy becomes a mixture of the base metal and the filler material. The properties of this “new” alloy determine to some extent the properties of the joint influenced by the degree of dilution of the weld metal by the base metal. Weld cracking is reduced by keeping base alloy dilution of the weld metal to a minimum. The MIG-Laser hybrid welded plates were welded using AWS ER 4043 filler material which gave ease of welding. Another point to be observed with regard to MLH welding is the reduction in welding speeds as the gap between the plates increased. Other important variables like power and weld current remained more or less constant. The three gaps were welded using a MIG-Laser hybrid welding machine at the African Laser Centre in Pretoria.

Table 4.5 shows the welding parameters used when welding MLH plates. Unlike the FSW and FSP processes, adjustments are done on the power input, the welding speed, the current, the voltage and the flow.
of the shielding gas during the welding process. With all the mentioned factors, the MLH process then becomes a bit more complicated when compared to the FSW and FSP processes.

Table 4.5: Welding parameters for MLH welded plates

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Power (kW)</th>
<th>Welding Speed (mm/min)</th>
<th>Current (Amperes)</th>
<th>Voltage (volts)</th>
<th>Shielding gas (l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>4</td>
<td>2000</td>
<td>170</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>2000</td>
<td>180</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>1500</td>
<td>180</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>A</td>
<td>4</td>
<td>2000</td>
<td>170</td>
<td>21</td>
<td>22</td>
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<tr>
<td>B</td>
<td>4</td>
<td>2000</td>
<td>170</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>2000</td>
<td>170</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>

Tensile and fatigue samples were obtained from these welded plates and micro-hardness testing and microstructure analysis performed on samples. The MIG-Laser hybrid welding process offers advantages like wider gap bridge ability and higher welding speeds compared to the friction stir welding process. Figure 4.4 shows the root of a MIG-Laser hybrid welded plate. The root height depends on many factors such as the current used and the gap width used during the welding process. It was noted that with 0mm gap the root height was 4mm higher than that welded at 1mm gap.
In some instances the resulting root height was just a millimeter and the MIG-laser hybrid welded plates had a v-shaped top surface finish, as seen in Figure 4.5, which could lead to crack initiation during fatigue testing and also reduce fatigue life of the sample if not polished. At some points on the weld area the thickness was inconsistent, especially at the end of the weld where there was a typical keyhole formed by the MIG-Laser Hybrid process. Weld ripples in the form of V’s can be seen and if not polished for fatigue testing would lead to failure. In normal butt welds, fatigue cracks usually begin at the weld ripples due to high stress concentrations.

Samples taken from MLH welded plates had to be machined to make fatigue and tensile samples but the later samples were not polished and...
were tested in the as received condition. Samples for the fatigue test were polished to remove surface defects where cracks could be initiated. Unlike steel, aluminium suffers a reduction in strength in the weld area and, when stressed, a welded aluminium structure will incur local deformation in the welded area first. The MLH process has better processing speeds when compared to competing processes. The use of the filler material makes it an expensive process as there is always a need for welding consumables in the form of the filler wire. Repeatability of this process is guaranteed, although the roots developed lacked consistency. The MLH process shows good results but is not environmental-friendly like the other two processes and a high level of skill and understanding of the MLH process is required from the operator.

4.6.3 Welds 19 - 21 - FSP Specimens

The plates used in the FSP process were skimmed on one side in order for the plates to lie parallel on the backing plate bar. The dimensions of the FSP tool have been discussed in Chapter 2 and Table 4.5 indicates the process parameters used in the Friction Stir Processing of MIG-Laser Hybrid welded plates. The table also shows how samples for mechanical testing were obtained from each processed plate. The dwell time for FSP was maintained at 20 seconds.
Table 4.6: Weld matrix for FSP

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Gap Width (mm)</th>
<th>Rotational Speed (rpm)</th>
<th>Welding Speed (mm/min)</th>
<th>Tensile Samples</th>
<th>Fatigue Samples</th>
<th>Microstructure Samples</th>
<th>Microhardness Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>0.5</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D1</td>
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<td>450</td>
<td>120</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B1</td>
<td>0</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A1</td>
<td>1</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A2</td>
<td>1</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B2</td>
<td>0</td>
<td>450</td>
<td>120</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D2</td>
<td>0</td>
<td>450</td>
<td>120</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Plates A, B and D were supplied by the African Laser Center with just two gap widths of 0mm and 1.0mm while plates C, E and F had gaps of 0mm, 0.5mm and 1.0mm respectively. The FSP concept tool was used to perform FSP on MIG-Laser hybrid welded aluminium alloy plates and, as this was not a “proper” welding process the dimensions of the new tool, had to be different from those of an FSW tool used to weld 6mm thick aluminium alloy plates.

The tool differed in that the emphasis was on improving the weld microstructure quality and to reduce stress concentration at the weld root bead. The welding speeds obtained during the weld trials in Chapter 3 were used for the FSP process. No other surface preparation was done on the plates after skimming and it was after this procedure that the plates were taken to the FSW machine for Friction Stir Processing.
The MIG-Laser Hybrid welded plates were measured on either end with a micrometer to check the thickness of the weld area. The thickness of the MLH welded plates was not constant across the length of the plate; the measurements are shown in Table 4.7. Once the thickness along the root bead was measured the plates were clamped onto the milling machine and then skimmed with a slab cutter on the opposite side of the root.

Table 4.7: Bead thickness measurements

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>[F] Bead Thickness (mm)</th>
<th>[L] Bead Thickness (mm)</th>
<th>Skimmed Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>5.95</td>
<td>7.94</td>
<td>7.22</td>
</tr>
<tr>
<td>C</td>
<td>5.95</td>
<td>8.33</td>
<td>7.77</td>
</tr>
<tr>
<td>F</td>
<td>5.95</td>
<td>7.73</td>
<td>7.76</td>
</tr>
<tr>
<td>D2</td>
<td>5.95</td>
<td>7.41</td>
<td>7.34</td>
</tr>
<tr>
<td>A1</td>
<td>5.95</td>
<td>7.6</td>
<td>7.03</td>
</tr>
<tr>
<td>B2</td>
<td>5.95</td>
<td>7.92</td>
<td>7.54</td>
</tr>
<tr>
<td>D1</td>
<td>5.95</td>
<td>7.9</td>
<td>7.13</td>
</tr>
<tr>
<td>A2</td>
<td>5.95</td>
<td>7.18</td>
<td>7.57</td>
</tr>
<tr>
<td>B1</td>
<td>5.95</td>
<td>7.96</td>
<td>8.35</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>7.52</td>
</tr>
</tbody>
</table>

The root developed as a result of the MLH process can be seen in front of the FSP tool which is mixed back into the weld, and excess material removed as a piece of wire. The FSP process attains lower welding temperatures when compared to the FSW and MLH welding processes. Figure 4.6 shows the FSP tool being used for FSP of MLH welded plates. The tool used for FSP had a smaller shoulder and pin geometries.
compared to the FSW tool. Unlike the FSW process, the FSP tool did not cause an improvement to misaligned plates like the FSW process.

Figure 4 6: The FSP process

In the FSP of the MLH welded plates the root bead formed as a result of the MLH process was displaced to the retreating side and the surface finish was comparable to that obtained by the FSW process using the tested MTRC FSP tool. Another point considered during FSP was the alignment of the plates to be processed and in some cases there was misalignment of the plates. This resulted in an unnecessary removal of material from the parent plate outside the welded area. The FSP tool exerted force on the MLH welded surface and if there was a groove on the welded plates the FSP tool would push the plate material and end up closing the grooved area.

The heat generated during the FSP process played an important role in subsequent weld properties as seen in the tensile results obtained from the process. The welding speeds are crucial in FSP as they could either increase or decrease the tensile strength of the weld as observed from the trial weld runs on 6082-T6 aluminium alloy plates. Another important aspect was that of dwell time which became an important factor when
one had a limited length to weld. In this regard it became critical for the operator to know the melting temperature of the material to be welded. The shoulder of the tool plays an important role on the duration of the dwell time. With a bigger shoulder it took about 10 seconds to reach 500°C whereas it took about 20 seconds to reach the same temperature with the FSP tool.

The FSW tool has a shoulder diameter of 25mm, the FSP tool concept has a shoulder diameter of 15mm which explains the differences in heat transferred during the dwell period. The major disadvantages of the other conventional welding processes when compared to FSW is that of misalignment. Unlike MLH welded plates with the FSW process a constant plate thickness is guaranteed along the weld area when using the same weld parameters. Another observation with the MLH welded plates is that unlike the FSW process there was a need for surface skimming of the weld root surface because of the poor surface resulting from the process.

4.7. TEMPERATURE PROFILES

Figure 4.7 depicts how samples were obtained from the welded plates for tensile and fatigue testing. The following graphs show the temperature profile of the FSP and FSW processes and also explain the concept of “stability temperature”. Experts in the FSW field suggest that samples should all be taken at a point where the temperature is stable to get comparable and good results from the welding process. A complete
A graphical representation of the temperature profiles from the welds is given in Appendix B.

**Figure 4.7: Temperature/distance profile for FSW**

**Temperature Profile for FSW Weld 1.12**

**Figure 4.8: Temperature/distance profile for FSP**

**Temperature Profile for FSP Weld 10.1 - Plate C**
It can be seen from Figures 4.7 and 4.8 that, at the beginning, the temperature gradient starts from room temperature and goes up as the welding process proceeds. Another aspect to be observed from the graphs is the difference between FSP and FSW temperature profiles. The welding temperatures for the FSW process are higher than those obtained in the FSP process the reason being that although the two processes are similar, FSP is not a welding process per se but a process that improves microstructural properties of the material. Temperature profiles for the two processes, namely FSW and FSP, are similar but the difference is with the stability temperature levels. The temperature profiles for the MLH process is thought to be different in that the laser does not need to move an x-distance to achieve normal welding temperatures.

The energy emitted at the beginning is the same as that emitted at the end of the weld, which makes getting samples for testing much easier than for the other two processes. It should be noted that with the FSP process, a temperature of 500°C, which is normally attained during FSW, is not reached for the duration of the welding process. Weld trials conducted using the FSP tool have shown that as the tool moves away from the starting point there is an increase in tensile strength of the weld and this is as a result of the influence of the stability temperature on the weld micro-structural properties.
4.8. FATIGUE LOAD APPLICATION AND TESTING

Fatigue testing was carried out using an *Instron 8801* servo-hydraulic testing machine, which is normally used for higher capacity fatigue and static testing of biomedical, advanced materials and manufactured components. The testing machine is equipped with an actuator of 100kN load capacity.

The load is applied by the bottom grip which forms a piston-like structure which is the only one allowed to move during all the testing procedures. The test pieces are mounted at both ends by means of the machine’s clamping mechanism on one side having a piston-like head. The piston produces fluctuating forces on the specimen by means of hydraulic pulsation. This consists of a motor-driven piston of variable stroke, which pulsates the oil passing to the main rams, inducing fluctuating pressure and hence force on the specimen.

During tensile testing the piston-like structure moves downwards at a constant speed until the sample fails in tension and with fatigue moves up and down at a high frequency that renders it difficult to actually see any movement at all. For the fatigue test, the load applied is adjusted by the operator but one should be careful not to apply a higher load than is necessary as some samples fail adjusting the amplitude. The consistency shown by the FSW process during tensile testing was influential in obtaining the optimum stress level to be used in fatigue testing.
The samples were subjected to a sinusoidal constant load with a stress ratio \( R = \frac{S_{\text{min}}}{S_{\text{max}}} \approx 0.1 \) and a test frequency of 40Hz. The ratio of minimum to the maximum is termed the stress ratio, \( R \), hence

\[
S_{\text{a}} = \frac{S_{\text{max}} + S_{\text{min}}}{2}
\]

\[
2S_{\text{c}} = S_{\text{max}} - S_{\text{min}}
\]

\[
R = \frac{S_{\text{min}}}{S_{\text{max}}}
\]

It should be noted that the aforegoing has only considered stress as being positive or negative in a general sense. In practice, fatigue can be generated in direct stress due to axial loading or bending or shear stress due to cyclic torsion or any combination of these [Benham and Crawford et al].

The cycle used in this research consisted of a combination of upper and lower limits within the static strength, which were both positive. The stress varied from a maximum tensile strength of 170MPa to zero [fluctuating cycle]. It has been found that if a material has been subjected to fluctuating stresses at fairly high frequencies, there is a tendency for failure to occur at a stress well below ultimate tensile strength value as obtained in a static test [Whitlow et al].

For this project, fatigue samples were all tested at an amplitude stress level of 170MPa and the tests carried out at room temperature. To determine the test stress level, the lowest load tested was 90MPa and increments of 30MPa were used up to 170MPa. Samples tested at
90MPa, 110MPa and 140MPa all resulted in runouts i.e. exceeded $2 \times 10^6$ cycles. The load was increased to 170MPa and the samples failed before 500,000 cycles, 95% of the FSW welded samples tested failed outside the heat affected zone on the parent material. The load was also adjusted to 190MPa and most samples failed before reaching 1000 cycles.

The testing of fatigue samples at 190MPa would have changed the testing approach from that of stress life to strain life. The results from the welded gaps varied between the processes used, and similarities were evident with each group tested. A minimum of five samples were tested for each process and gap width. All the fatigue samples were polished with 1200 grit sandpaper and sharp edges removed.

### 4.8.1. Calibration of Fatigue testing machine

A fatigue specimen was used in the calibration of the Instron 8801 servo-hydraulic machine and the specimen had a strain gauge fixed to it connected to the strain recorder as shown on the following pages in Figure 4.10. Every change in strain and force was recorded. Calibration refers to the process of setting the magnitude of the output (or response) of a measuring instrument to the magnitude of the input property or attribute within specified accuracy and precision [wikipedia]. Calibration is important for any mechanical equipment expected to give exact measurements and correct output and in this case stress values.
Five sets of tests were performed using the same fatigue sample and a curve was plotted which gave similar trends with minimum deviation of the lines (see Figure 4.9).

![CALIBRATION GRAPH FOR 6082-T6 Aluminium Alloy](image)

**Figure 4.9: Calibration curve**

For all the five sets of calibration there was a similar trend to force versus strain which implies that the equipment tested gives out correct measurements. The machine setup is shown in Figure 4.10; the fatigue sample is fixed on the machine with wires from the strain gauge connected to the strain recorder. After every movement of the piston the measurements were taken and later used to plot the calibration graph.
4.9. Specimen preparation

4.9.1 Tensile samples

- Strips of $26 \times 240\text{mm}$ were marked on the welded plate; holes were drilled to mount the specimens on the CNC machine as shown in Figure 4.11.
Figure 4.11: A typical tensile sample

- A set of four strips were machined at a time on the CNC machine to a final size of $20 \times 190 \text{mm}$ and ASTM E8 standard used as a reference for tensile samples.

- The samples were to be tested in the as-welded condition i.e. no polishing was done on the samples, but sharp edges were removed. The first three samples from the plate shown in Figure 4.12 are for tensile and the remaining five for fatigue testing.

- All samples were taken at a distance of $100 \text{mm}$ from the start of the weld. The reason is that temperature rises up from the beginning of the weld and stabilizes at about $100 \text{mm}$ from the start and afterwards temperature remains constant.
Figure 4.12 shows an FSP plate and how the samples were obtained based on the temperature profiles obtained. Tensile and fatigue samples are indicated on the Figure.

![Specimens for tensile and fatigue testing](image)

Owing to a limited supply of aluminium alloy material from the ALC, some samples were taken from a distance of 50mm from the beginning of the weld. This was done because the plates used to obtain MLH test specimens had to provide samples for FSP as well.

### 4.9.2 Fatigue samples

- Strips of $36 \times 240\,mm$ were cut from the welded plates and holes drilled to mount the specimens on the CNC machine.
- The ASTM E466-96 standard was used as a reference in the machining of samples which were machined to a final size of $30 \times 202$. 
Fatigue samples were first skimmed on the milling machine to remove burrs. The ends were milled off on the milling machine to remove the holes used to clamp the samples for CNC machining.

Samples were then polished using 600-grit sandpaper and water. They were marked with an engraver on both sides for identification, and sandpaper was used to polish round and smooth all corners.

**4.9.3 Microstructure and microhardness samples**

 Samples were cut through the cross section of the weld and mounted in a hot mount polymeric resin.

The samples were then ground on the Struer’s piano 220-grit to flatten them and also to expose the area to be examined. After
polishing, the samples were etched using a sodium hydroxide solution (NaOH) to reveal the microstructure.

- All the samples were identified and matched with the correct welding procedure i.e., FSP, FSW and MLH.
- Samples for the three processes were measured from one reference point for comparison purposes.

A micro-hardness profile was performed on the MLH, FSP and FSW welded samples. The testing was done through the cross section of the samples using a standard Vickers micro-hardness (Matsuzawa MHT2) machine perpendicular to the welding direction at 3mm from the root face with a 500gf applied for 15s. The indentations were all 0.5mm apart and a total length of 22mm was covered. This was done to generate a hardness profile over the whole specimen. The hardness test is a measure of the resistance to permanent deformation of the material and therefore it can be correlated with the strength of the material [Bussu & Irving et al].

4.9.4. Fatigue

Information on Specimen preparation

- The total welded length /distance was 330mm and samples were obtained at a distance of 80mm from the start of the weld and up to 30mm before the tool retracted. This was done to exclude possible deviation from steady state during start and stop.
After machining on the CNC machine, sharp edges were removed in preparation for skimming and polishing.

Samples were skimmed on the welded side by 0.4mm and then polished by 600-grit paper all around until the surface was smooth and no tool marks were visible. All the samples were engraved on the side for identification purposes.

**Conditions of specimens prior to fatigue testing**

The samples were polished and then kept at room temperature wrapped in soft paper to avoid corrosion pitting.

**Fatigue Test**

The fatigue specimens were tested at a single stress level in order to compare the fatigue life of the three welding processes, namely Friction Stir Welding (FSW), MIG-Laser Hybrid Welding and Friction Stir-MIG-Laser Hybrid Welding.

**Ambient conditions**

The testing was done at room temperature with temperatures ranging from 26°C to 34°C for the duration of the testing and with a relative humidity of 60%.
4.9.5. **Tensile**

**Information on Specimen preparation**

Samples were tested in the as welded condition. Data was retrieved from the computer and used to plot graphs of stress versus extensions. The data was used to determine the yield strength of the specimens.

**Material and sample Identification**

The tensile samples were all marked on the sides and on the surface to avoid sample mix-up. The material used in all the specimens was the 6082-T6 Aluminium Alloy.

**Specimen test section dimension(s)**

The specimens had a rectangular geometry with a width of ±12.89mm and a thickness ±6mm. The yield strength for each sample was obtained from the tensile data as the computer failed to give out the values. The tensile strength was taken as the maximum load applied during the test and this was used in obtaining all the tensile strength values for all the samples. The specimens had a gauge length of 50mm before testing commenced, and this was used as a reference when measuring the elongation before and after fracture.

4.10. **FRACTURE SURFACE OBSERVATION**

**The Scanning Electron Microscope (SEM)**

The SEM allows an indirect observation of the fatigue surface in all ranges of magnification. The large depth of field of the SEM is a very
important benefit for fractographic investigations. Fracture surfaces can be observed with an SEM almost without any special preparation; nevertheless, the specimen should be clean. Cleaning can be done mechanically by rinsing in ultrasonic cleaner or in chemical reagents or electrolytes. The two last methods are used where the specimen surface is oxidised to such a degree that the oxide film changes surface topography or gathers electrostatic charge, making the observation impossible, since the necessary condition for investigation by means of SEM is electric conductivity of the specimen, at least in the surface layer. Figure 4.14 shows the SEM used for the observation of fracture surfaces.

![SEM Image](Image)

Figure 4.14: The JEOL JSM-6380 Scanning Electron Microscope

### 4.11. SUMMARY

This chapter explains the experimental setup which is about how the data was obtained. The machine used in the welding of the plates was introduced and its operation discussed. The material characteristics of
the Al-Mg-Si alloy used, plate preparation for the welding process, together with tools used in the welding of FSP and FSW processes form part of the discussion. The temperature profiles obtained as part of the welding data from the FSW machine are discussed and their importance on welds and the whole welding process highlighted. The method used to get samples from welded plates and how they are prepared for mechanical testing as well as the information that should be provided when reporting tensile data is given.
CHAPTER 5

RESULTS AND DISCUSSION

5.1. INTRODUCTION

The aim of this study is to determine the influence of Friction Stir Processing (FSP) on the mechanical properties of MIG-Laser Hybrid welded (MLH) 6082-T6 aluminium alloy joints, and to compare the results to MLH and Friction Stir Welded (FSW) joints. The Friction Stir Welding process has proved to be the best method available for joining aluminium alloys when high weld integrity is required and it was anticipated that, by introducing properties of FSW into MIG-Laser Hybrid welded 6082-T6 aluminium alloy joints in the form of FSP, it would cause an improvement in the mechanical properties of the weld. In this chapter the effect of FSP on MIG-laser hybrid weld joints will be discussed. The analysis that forms part of the discussion includes fractography, tensile, fatigue and microhardness data. It was established that the FSP process reduced the ultimate tensile strength of MLH weld joints but caused an improvement to the fatigue life of the joints by more than 30%.

5.2. TENSILE TESTING

An average of three samples per gap setting was taken from each welding process. The results from tensile testing are discussed relative to each process and compared with other competing processes. The three competing processes (i.e. Friction Stir Processing, Friction Stir
Welding and MIG-Laser Hybrid welding) were grouped together on one graph to compare each process relative to other processes. Figure 5.1 shows the tensile data obtained from testing the parent material and Table 5.1 shows results obtained in tensile testing of the parent material. The T6 material had a 0.2% proof strength average of 303 MPa, and an average ultimate tensile strength of 326 MPa. The elongation (A50) was 14%.

According to Scialpi et al [2006] the higher tensile strength of the parent material is due to the T6 heat treatment when compared to the samples welded with conventional welding methods, namely FSW and MLH welding processes.
Table 5.1: Tensile results for parent material

<table>
<thead>
<tr>
<th></th>
<th>0.2% Proof Stress (MPa)</th>
<th>Ultimate Tensile Stress (MPa)</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent 1</td>
<td>296.6</td>
<td>330</td>
<td>14</td>
</tr>
<tr>
<td>Parent 2</td>
<td>303.9</td>
<td>322</td>
<td>14.4</td>
</tr>
<tr>
<td>Parent 3</td>
<td>308.7</td>
<td>327</td>
<td>14</td>
</tr>
<tr>
<td>Average</td>
<td>303</td>
<td>326</td>
<td>14.1</td>
</tr>
</tbody>
</table>

5.2.1. 0mm gap

Figure 5.2 shows the typical tensile data of the three processes investigated namely FSP, FSW and MLH for the 0mm gap.

Figure 5.2: Tensile results [FSP vs. FSW vs. MLH] – 0mm gap
Table 5.2 shows the values obtained from tensile testing. The FSW T6 material had a 0.2% proof stress of 143MPa, an ultimate tensile strength of 223MPa and an elongation of 7.18%. Weld efficiency is defined as the percentage ultimate tensile strength ratio of the welded samples to that of the parent plate. The weld efficiency was 68% for FSW welded samples. FSP welded samples had a 0.2% proof stress of 144MPa, a tensile strength of 237MPa and elongation was 6.4%. The weld efficiency was 73%. MLH welded samples had a 0.2% proof stress of 143MPa, a tensile strength of 247MPa and an elongation of 3.18%. The weld efficiency was 76%. A graph containing tensile data for all the samples tested at 0mm, 0.5mm and 1mm gap is given in Appendix C.

Table 5.2: Tensile results for 0 gap

<table>
<thead>
<tr>
<th>Process</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
<th>Weld Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSW</td>
<td>143</td>
<td>223</td>
<td>7.18</td>
<td>68</td>
</tr>
<tr>
<td>FSP</td>
<td>144</td>
<td>237</td>
<td>6.4</td>
<td>73</td>
</tr>
<tr>
<td>MLH</td>
<td>143</td>
<td>247</td>
<td>3.18</td>
<td>76</td>
</tr>
</tbody>
</table>

It is clear from the results obtained that the tensile properties of all the joints are lower than those of the parent material and the FSW samples showed the lowest ultimate tensile strength amongst the processes tested at 68% of the base material. The FSW welds had the highest ductility of the processes evaluated at 7.18%. The “new alloy” [AWS ER 4043 + 6082-T6] developed during the MLH welding process resulted in the lowest percentage elongation (3.18%) of MLH samples.

The 4043 aluminium filler wire is an aluminium wire with 5% silicon and it was developed specifically for welding the 6000 series aluminium alloys.
Mechanical properties such as yield, tensile strength and elongation are affected by the choice of aluminium base and filler alloys. The 4043 used in the welding provides lower ductility than other available filler materials like 5356 and the filler weld strength is mostly dependent on the composition of the aluminium filler alloy used (weldreality et al).

The MLH welded joints fractured in the area between the Heat Affected Zone (HAZ) and weld root as a result of porosity in the weld metal. The MLH process had the highest ultimate tensile strength (247MPa) which was equivalent to 76% of the parent material’s UTS.

The FSP process mixed the filler alloy material together with the parent material over a larger area and introduced a heat treatment process. Heat treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improved machining, formability and to restore ductility after a cold working operation. It is thus an enabling manufacturing process that assists other manufacturing processes and also improves product performance by increasing strength or other desirable characteristics.

The UTS was about 73% of the parent material which was higher than for FSW welded joints which were 68% of the parent material. The
introduction of FSP to MLH welded plates improved ductility of the material by up to 48%, as shown in Figure 5.2.

**5.2.2. 0.5mm gap**

The tensile results obtained for samples tested for the 0.5mm gap are shown in Figure 5.3 with the summary of major tensile results given in Table 5.3. The full graph is given in Appendix C.

![Tensile Results [FSP vs FSW vs MLH]](image)

*Figure 5.3: Tensile results [FSP vs. FSW vs. MLH] – 0.5mm gap*

Table 5.3 shows results obtained in tensile testing of the welded plates from the three processes. FSW material had a 0.2% proof stress of 146MPa and a tensile strength of 226MPa. The elongation and weld...
efficiency was 7.1% and 69% respectively. FSP welded samples had a 0.2% proof stress of 145MPa and a tensile strength of 216MPa. The elongation of the material was 5.2% with a weld efficiency of 66%. MLH welded samples had a 0.2% proof stress of 145MPa, a tensile strength of 221MPa and an elongation of 3%. The weld efficiency was 68% in the MLH welded condition.

<table>
<thead>
<tr>
<th>Process</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
<th>Weld Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSW</td>
<td>145</td>
<td>226</td>
<td>7.1</td>
<td>69</td>
</tr>
<tr>
<td>FSP</td>
<td>145</td>
<td>216</td>
<td>5.2</td>
<td>66</td>
</tr>
<tr>
<td>MLH</td>
<td>145</td>
<td>221</td>
<td>3</td>
<td>68</td>
</tr>
</tbody>
</table>

The MLH process had the lowest UTS for the 0.5mm gap and also the lowest elongation when compared with other processes. Even though the UTS is amongst the lowest, it is still acceptable at 68% of the parent material. According to literature concerning all heat treatable aluminium alloys the weld shows acceptable ultimate tensile strength when the UTS of the specimen is higher than 66% of the base material [Chao et al 2003]. The FSP process resulted in an increase in ductility when compared to MLH welded samples for the same gap. The FSP welded samples for this gap meet the minimum requirements set for heat treatable alloys with a UTS of 66% of the parent material.

The FSP process had the lowest UTS for the 0.5mm gap at 216MPa, which is about 66% of the parent material’s UTS. The FSP samples had a better percentage elongation than MLH welded samples at 5.2% compared to 3%. The FSW welded samples had the highest UTS values.
at 226MPa which is equivalent to 69% of the parent material. The percentage elongation is the best at 7.1% and the highest in the processes evaluated for this gap. The results obtained with tensile testing agree with those obtained by other researchers in friction stir and fusion welding research [Ericsson and Sandstrom et al 2006].

5.2.3. 1mm gap

The average tensile results obtained from samples tested for the one millimetre gap are shown in Figure 5.4 with a summary of all the major tensile results given in Table 5.4.

FSW welded samples had a 0.2% proof stress of 148MPa and a tensile strength of 228MPa. The elongation was 7.2%. The weld efficiency was 70%. FSP welded samples had a 0.2% proof stress of 147MPa, a tensile strength of 219MPa and an elongation of 6.4%. The weld efficiency was
67%. MLH welded samples had a 0.2% proof stress of 146MPa, a tensile strength of 245MPa and an elongation of 3.2%. The weld efficiency was 75%.

Table 5.4: Tensile results for 1.0mm gap

<table>
<thead>
<tr>
<th>Process</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
<th>Weld Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSW</td>
<td>148</td>
<td>228</td>
<td>7.2</td>
<td>70</td>
</tr>
<tr>
<td>FSP</td>
<td>147</td>
<td>219</td>
<td>6.4</td>
<td>67</td>
</tr>
<tr>
<td>MLH</td>
<td>146</td>
<td>245</td>
<td>3.2</td>
<td>75</td>
</tr>
</tbody>
</table>

The results obtained for this gap for the MLH process had the highest UTS for the 1mm gap and the UTS was 75% of the parent material. Within the range of gaps tested it seems that the gap width played a minor role in the final weld tensile properties. The MLH process had the lowest percentage elongation which was 23% of the parent material.

The FSP process had the lowest tensile strength at 219MPa which is 67% of the parent material but still acceptable for heat treatable alloys. The percentage elongation increased from 23% of the parent material with the MLH process to 51% of the parent material’s with the introduction of the FSP process.

The FSW process had the second highest UTS at 228MPa which is 70% of the parent material. The percentage elongation was the highest at 57% of the parent material. Based on the mechanical properties obtained in testing, the 1mm gap would still be acceptable as it results in a positive increase in the UTS and ductility of the welded joints. All the
specimens failed outside the weld area in the heat-affected zone and fractured at 45° to the horizontal.

5.2.4 SUMMARY-Tensile Data

Table 5.5 shows the combination of all the tensile test data and efficiency obtained for the gaps tested. The table shows a clear variation in elongation and weld efficiency amongst the three processes. The graph obtained in tensile testing of the parent material behaved differently when compared to those of welded specimens and at some instances the elongation was double that of welded specimens.

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>Process</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
<th>Weld Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>FSW</td>
<td>143</td>
<td>223</td>
<td>7.18</td>
<td>68</td>
</tr>
<tr>
<td>0.5</td>
<td>FSW</td>
<td>146</td>
<td>226</td>
<td>7.1</td>
<td>69</td>
</tr>
<tr>
<td>1</td>
<td>FSW</td>
<td>148</td>
<td>228</td>
<td>7.2</td>
<td>70</td>
</tr>
<tr>
<td>0</td>
<td>FSP</td>
<td>144</td>
<td>237</td>
<td>6.4</td>
<td>73</td>
</tr>
<tr>
<td>0.5</td>
<td>FSP</td>
<td>145</td>
<td>216</td>
<td>5.2</td>
<td>66</td>
</tr>
<tr>
<td>1</td>
<td>FSP</td>
<td>147</td>
<td>219</td>
<td>6.4</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>MLH</td>
<td>143</td>
<td>247</td>
<td>3.18</td>
<td>76</td>
</tr>
<tr>
<td>0.5</td>
<td>MLH</td>
<td>145</td>
<td>221</td>
<td>3</td>
<td>68</td>
</tr>
<tr>
<td>1</td>
<td>MLH</td>
<td>146</td>
<td>245</td>
<td>3.2</td>
<td>75</td>
</tr>
<tr>
<td>- Parent</td>
<td></td>
<td>303</td>
<td>326</td>
<td>14.1</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 5.5 shows weld efficiency versus the gap variation from the three processes evaluated. The FSW process showed a linear trend whereas the MLH and FSP processes exhibit a hyperbolic trend. The weld efficiency of the MLH and FSP processes was not as consistent as that obtained with the FSW process. The FSP and MLH processes have the best weld efficiencies at 0mm gap and the FSW process has the lowest
efficiency for the same gap. The weld efficiency of the FSW process increased with gap whilst the other processes decreased at 0.5mm and 1mm gaps respectively.

![Weld Efficiency vs Gap (mm)](image)

The MLH process had the highest weld efficiency for the 0mm gap followed by FSP and FSW processes respectively. The MLH and FSP welded samples follow a similar trend for the 0mm and 0.5mm gaps in which there is a striking difference in weld efficiencies from 0.5mm to the 1mm gap for the MLH process.

From published literature an increase of a 0.5mm in gap width should be accompanied by a reduction of 22%-25% in welding speeds [see Figure
2.20]. This was not done with the MLH welded plates as the speed used for 0mm gap was maintained for the 0.5mm gap as well. This caused a reduction in weld tensile strength for the 0.5mm gap which could have been avoided. The introduction of FSP reduced the strength of the MLH welded plates considerably. The effect of reducing welding speeds resulted in a slight reduction in tensile strength as shown by the 1mm gap when compared to the 0mm gap. The FSP process refines the grain structure of the MLH welded plates resulting in improved fatigue life but reduced tensile strength as discovered in the current research. All the FSP welded gaps have weld efficiencies lower than those obtained from testing MLH welded specimens.

Prior to the speeds used for this analysis, welding speeds of 400rpm and 100mm/min were used for FSW and they resulted in UTS that was 10% lower than results analysed here. The speeds were then adjusted to 500rpm and 80mm/min and there was an increase in the UTS of the welded joints.

The change in welding speeds caused an increase in the stability temperature acquired when welding the material. An increase in welding speeds resulted in an increase in heat input which played a major role in the final weld mechanical and metallurgical properties of the weld. This occurred mainly from improved grain refinement due to the amount of heat dissipated per unit area which resulted in the solution heat treatment process on the material.
Fuller et al. reported that the ability of a given alloy to be deformed during friction stir processing or welding depends on the alloy’s elevated temperature flow stress. The strength of the weld area depends on the fusion of the filler material with the parent material, and any irregularities in this “new alloy” weakens the joint strength. A possible reason could be the change in welding speeds when compared to other gaps. The introduction of a gap without an increase in welding speed increases penetration which then results in a larger underbead and a reduction in tensile strength of fusion welds [Claus & Bagger et al. 2005].

The FSP process was carried out at the weld root area to improve the weld fatigue properties and resulted in the lowest UTS values amongst the three processes. Figure 5.6 illustrates the elongation of welded samples versus gap width and the differences between the three processes are clearly visible.
The MLH welded samples had the lowest elongation as observed from the figure. FSP resulted in more than 50% improvement to the MLH welded samples and there was a reduction in elongation for the 0.5mm gap for both FSP and MLH processes. The effect of not reducing the speed by 22%-25% for the 0.5mm gap is evident in MLH and FSP welded specimens as illustrated by the reduction in elongation. There seems to be a close relation in gaps tested as far as elongation is concerned for all the processes.

The FSP process has been used successfully to improve superplastic properties in aluminium alloys resulting in alloys to be deformed easier. Owing to microstructural refinement, the material becomes more ductile resulting in high strain superplasticity of the 6082-T6 aluminium alloy.
The FSW process maintained a consistent elongation for all gaps evaluated. The FSW process results in thermal softening of the material compared to the MLH process resulting in the material having a higher elongation. The presence of a gap seems to play no role on the elongation of the material in all the welding processes. Figure 5.7 shows the location of tensile fractures from the three welding processes: (a) shows an MLH fracture which failed right at the centre of the weld (in the filler material): (b) is an FSP fracture which failed right at the centre of the weld. A typical FSW fracture is shown in Figure 5.7(c) where the fracture position is outside the welded area in the HAZ. Although difficult to locate, there seems to be a correspondence between fracture position and position of minimum hardness for AA 6082 [Svenson and Karlson et al].

Figure 5.7: MLH (a), FSP (b) and FSW (c) fracture locations
The failure of weld 5.7(a) at the centre is due to the pores resulting from welding aluminium with the hybrid process. The more pores the smaller the effective cross-sectional area which therefore fails at lower stress. This results in uneven microstructural distribution in the weld zone resulting in areas susceptible to failure in tension. Another major influence in weld zone strength is the shielding gas arrangement which becomes a deciding factor since it influences molten pool behaviour, vapour gas and the solidification process. The choice of shielding gas is of utmost importance as it reduces spatter but usually Helium is the first choice as it helps avoid excessive plasma absorption. Helium was used during the MLH welding process of the specimens.

The strength of the FSP weld 5.7(b) depends mainly on the factors mentioned for the MLH welded specimens as it is merely process used to address inadequacies developed by other processes. If the choice of shielding gas, shielding gas arrangement, and other parameters are taken care of a good FSP joint is guaranteed.

The fracture location for an FSP joint depends entirely on the strength and ductility of the MLH weld as it becomes the first side to fail due to elongated grains resulting from the process. Once the MLH-welded half has failed the FSP processed side holds on a bit longer before failing and its fracture location is dependent on the MLH-welded side.
5.3. FATIGUE TESTING

5.3.1. Results and discussion

The welded specimens were all tested at a load below the yield strength of the aluminium alloy 6082-T6 parent plate. The cross sectional area of the samples was taken into consideration when setting up the load for each sample tested and the load was adjusted until it corresponded to the chosen stress level. Table 5.6 shows the fatigue life for the parent plate.

Table 5.6: Fatigue results for the parent plate

<table>
<thead>
<tr>
<th>Gap Width (mm)</th>
<th>Amplitude Stress (MPa)</th>
<th>Number of cycles to failure</th>
<th>Average number of cycles</th>
<th>Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 869</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>293</td>
<td>26 719</td>
<td>26 428</td>
<td>8277</td>
<td></td>
</tr>
<tr>
<td>30 696</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 862</td>
<td></td>
<td>29 374</td>
<td>17639</td>
<td></td>
</tr>
<tr>
<td>277</td>
<td>24 223</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 038</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 553</td>
<td>46 591</td>
<td>7924</td>
<td></td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>42 629</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56 420</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>139 178</td>
<td>97 799</td>
<td>82756</td>
<td></td>
</tr>
<tr>
<td>193 234</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>244</td>
<td>151 234</td>
<td>172 234</td>
<td>42000</td>
<td></td>
</tr>
<tr>
<td>340 520</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>551 242</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>228</td>
<td>578 799</td>
<td>459 899</td>
<td>238279</td>
<td></td>
</tr>
<tr>
<td>481 644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>347 293</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1 000 000</td>
<td>1 000 000</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1 000 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 484 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 630 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>195</td>
<td>724 424</td>
<td>1 427 000</td>
<td>1 012843</td>
<td></td>
</tr>
<tr>
<td>617 157</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 167 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.7: Fatigue results for the FSW process

<table>
<thead>
<tr>
<th>Gap Width (mm)</th>
<th>Amplitude Stress (MPa)</th>
<th>Number of cycles to failure</th>
<th>Average number of cycles</th>
<th>Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>170</td>
<td>295 358</td>
<td>189 341</td>
<td>338 347</td>
</tr>
<tr>
<td>0.5</td>
<td>170</td>
<td>202 376</td>
<td>235 173</td>
<td>179 879</td>
</tr>
<tr>
<td>1</td>
<td>170</td>
<td>175 446</td>
<td>106 327</td>
<td>127 834</td>
</tr>
</tbody>
</table>

Range* = Maximum number of cycles - Minimum number of cycles

The range represents the difference in fatigue life between the highest and lowest fatigue life values obtained in the test. From the FSW welded sample results the 0mm gap showed the longest life followed by the 0.5mm gap and the shortest life being the 1mm gap. The fatigue life of 0mm gap was found to be 68% higher than that of the 1mm gap and the 0.5mm gap was found to be 15% higher than that of 1mm gap. The FSW process resulted in a decrease in fatigue life as the gap between the plates increased.
Table 5.8: Fatigue results for the MLH process

<table>
<thead>
<tr>
<th>Gap Width (mm)</th>
<th>Amplitude Stress (MPa)</th>
<th>Number of cycles to failure</th>
<th>Average number of cycles</th>
<th>Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>170</td>
<td>228 022</td>
<td>181 908</td>
<td>166 752</td>
</tr>
<tr>
<td></td>
<td></td>
<td>171 957</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>170</td>
<td>24 368</td>
<td>106 349</td>
<td>299 334</td>
</tr>
<tr>
<td></td>
<td></td>
<td>121 330</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 270</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>170</td>
<td>485 403</td>
<td>136 731</td>
<td>471 322</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 963</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Range* = Maximum number of cycles - Minimum number of cycles

The fatigue life of the 0mm gap was found to be the highest in all the MLH welded gaps and the lowest being the 0.5mm gap which also had the lowest UTS during tensile testing. The fatigue life of the 0mm gap was 71% higher than 0.5mm gap which was an indication of the disadvantage brought about by the introduction of a gap.

The fatigue life of the 0mm gap was found to be 33% higher than that of the 1mm gap. The two gaps (i.e. 0mm and 0.5mm) were welded at 2000mm/min and the 1mm gap at 1500mm/min. To keep the strength and fatigue life of the welded joints acceptable in MIG-Laser Hybrid welded plates the processing speeds were reduced as the gap between the plates was increased but this was not done with the 0.5mm gap.
The majority of the tested samples had pores in the weld metal which corresponds to literature as one of the major problems encountered when welding aluminium alloys by fusion processes. All the MLH welded samples failed at the centre of the fusion weld (i.e. in the filler material). The welding parameters used for 0mm and 0.5mm gaps were the same and this could be one of the reasons for the reduction in fatigue life with the introduction of the gap between the plates.

Table 5.9 shows the three gaps evaluated with the fatigue test for the FSP process.

Table 5.9: Fatigue results for the FSP process

<table>
<thead>
<tr>
<th>Gap Width (mm)</th>
<th>Amplitude Stress (MPa)</th>
<th>Number of cycles to failure</th>
<th>Average number of cycles</th>
<th>Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>170</td>
<td>153 977</td>
<td>150 750</td>
<td>222 108</td>
</tr>
<tr>
<td></td>
<td></td>
<td>254 318</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>170</td>
<td>42 994</td>
<td>253 645</td>
<td>346 633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>168 713</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>389 627</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>170</td>
<td>193 439</td>
<td>243 555</td>
<td>195 581</td>
</tr>
<tr>
<td></td>
<td></td>
<td>351 296</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>320 253</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Range* = Maximum number of cycles - Minimum number of cycles
The 0mm gap had the lowest average fatigue life with 150 750 cycles and one of the samples had the lowest number of cycles at 32 210. The 0.5mm gap had the highest average fatigue life followed by the 1mm gap. These results indicate the positive effect brought about by the introduction of FSP to MLH welded joints. Table 5.10 shows the three processes compared namely FSW, FSP and MLH evaluated with the fatigue test, and the average number of cycles formed the basis of comparison for the three processes for 0mm gap.

<table>
<thead>
<tr>
<th>Table 5.10: Fatigue results for all gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gap</strong></td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>0mm Gap</td>
</tr>
<tr>
<td>Average number of cycles</td>
</tr>
<tr>
<td>0.5mm Gap</td>
</tr>
<tr>
<td>Average number of cycles</td>
</tr>
<tr>
<td>1mm Gap</td>
</tr>
<tr>
<td>Average number of cycles</td>
</tr>
</tbody>
</table>

Range = Maximum number of cycles - Minimum number of cycles

From the results obtained, the FSW process had the highest fatigue life amongst the three processes compared. The FSW welded samples had a fatigue life that was 62% higher than the MLH welded samples. The FSW welded samples had a fatigue life that was 96% higher than FSP welded samples.
The 0.5mm gap fatigue life results show a marked improvement compared to the 0mm gap. The FSP process has the highest fatigue life amongst the gaps analysed. The fatigue life of the FSP process is 138% higher than that obtained with the MLH process and 25% higher than the FSW process. The benefits of introducing the FSP process are evident with the 0.5mm gap and there is a huge improvement in fatigue life. The FSP process has the highest fatigue life for the 1mm gap with 243,555 cycles. The fatigue life of the FSP process was 78% higher than that obtained with the MLH process. The same process has a fatigue life that was 39% higher than that obtained with the FSW process.

5.3.2. SUMMARY-Fatigue Data

The MLH process resulted in a decrease in fatigue life as the gap between the welded plates increased and the same applied to the scatter. From the results obtained it was clear that for the MLH welded specimens, the 0mm gap produced the best results. The FSP process resulted in an increase in fatigue life as the gap between the plates was increased. The 0.5mm and 1mm gaps show a remarkable improvement (28%) in the fatigue life based on the results obtained with the MLH process. However, when compared with the 0mm gap result there existed a decrease in life of 42% (0.5mm gap) and 25% (1mm gap). Figure 5.8 shows the fatigue life versus gap for the three processes. There is a decrease in fatigue life as the gap between the plates increase with the FSW process and the inverse of that happened with the FSP samples.
These results help identify the influence the addition of a gap had on the integrity of the joints evaluated. The fatigue life of MLH welded samples decrease as well as exhibiting an increase in the gap between the plates. The FSW process had the best fatigue life amongst the three processes for 0mm gap only and the other gaps were dominated by the FSP process.

![Fatigue life vs. Gap](image)

**Figure 5.8: Fatigue life vs. gap (at Stress =170MPa)**

The fatigue life of FSW welded specimens was the best for 0mm gap and reduced proportionally as the gap between the plates increased. The MLH specimens had a fatigue life that was 18% higher than FSP specimens for the 0mm gap. The FSP specimens performed better than MLH and FSW specimens for 0.5mm and 1mm gaps. With the FSP process all the fatigue failures started at zones of low hardness, that being at the MLH welded zone.
The FSP failures initiated on the MLH welded side and finally fractured on the friction stir processed side. The FSW welded specimens failed outside the weld area in both tensile and fatigue testing, inside the thermo mechanical affected zone on the retreating side which also experienced a decrease in hardness. FSP was instrumental in improving the fatigue life of MLH welded joints. Figure 5.9 below shows the difference between FSP, FSW and MLH fatigue failure locations.

Figure 5.9: Fractures from FSP (a), MLH (b) and the FSW (c) processes [dotted lines=weld region]
The FSP welded sample failed at the centre of the weld. The MLH welded sample failed at the centre of the weld with a brittle-like failure appearance. Observations from Fractography are discussed in section 5.4. The FSW welded sample failed outside the HAZ area on the parent plate and those that failed nearer to the weld failed at the HAZ. The welded specimens were all tested at a load below the yield strength of the aluminium alloy 6082-T6 parent plate (at about 56% of yield) as most design specifications recommend use within the elastic range. The yield strength of welded samples tested averaged 140MPa for all the welding processes evaluated. Therefore, theoretically the welded samples were loaded in the plastic range. Yet testing of these samples at lower loads (i.e. 140MPa) resulted in run-out. Therefore hardness was used to determine the magnitude of loading the specimens experienced.

Hardness has proved to be a better measure of strength since it is not dependent on cross sectional area and therefore not influenced by voids, gas porosity, onion skin defects, etcetera. According to Nobre et al [2000], due to the fact that there is a correlation between hardness and strength, the change in yield strength ($\sigma_y$), relative to the original yield strength ($\sigma_{yo}$) can easily be estimated based on the change in hardness ($\Delta HV$), relative to the hardness of original material. The estimated yield strengths of the various zones of the weld regions were calculated as follows: FSP samples failed in the centre of the weld area (for fatigue)
and the average hardness across the centre [4mm] is approximately 60.31HV.

\[ \Delta HV = HV_o - HV_{FSF} \]
\[ \Delta H_v = 95 - 60.31 \]
\[ \Delta H_v = 34.09 \]

Therefore the difference in yield strength of the zone which experienced failure is thus:

\[ \frac{\Delta \sigma_y}{\sigma_{ys}} = \frac{\Delta HV}{HV_o} \]
\[ \frac{\Delta \sigma_y}{303} = \frac{34.09}{95} \]
\[ \Delta \sigma_y = 108.72\text{MPa} \]

Therefore new estimated yield strength of material in the centre zone is:

\[ = 303 - 108.72 \]
\[ = 194.28\text{MPa} \]

The applied load of 170MPa is 87.5% of the \( \sigma_y \) (yield strength) of the weld material. **MLH** samples also failed in the centre of the weld area (for fatigue), therefore average HV from -2 to 2mm from the centre equals 78.4 HV:

\[ \Delta HV = HV_o - HV_{MLH} \]
\[ \Delta HV = 95 - 78.4 \]
\[ \Delta HV = 16.6 \]
\[
\frac{\Delta \sigma_y}{\sigma_{yw}} = \frac{\Delta HV}{HV_0}
\]

\[
\frac{\Delta \sigma_y}{303} = \frac{16.6}{95}
\]

\[\Delta \sigma_y = 52.95\]

Therefore new estimated yield strength of material in the centre zone

\[= 303 - 52.95\]

\[= 250.05 \text{MPa}\]

The applied load of 170MPa is 68% of \(\sigma_y\) (yield strength) of the weld material. FSW samples failed outside the weld area (for fatigue). The average \(H_v\) across the centre [4mm] equals 62.7HV. The FSW welded samples were included in this analysis for comparison purposes, and as a point of reference, as the process has proved to be the best when welding aluminium.

\[\Delta H_v = H_{yo} - H_{v, FSW}\]

\[\Delta HV = 95 - 62.7\]

\[\Delta HV = 32.3\]

So the zone of fatigue failure's change in yield strength is thus:

\[
\frac{\Delta \sigma_y}{\sigma_{yw}} = \frac{\Delta HV}{HV_0}
\]

\[
\frac{\Delta \sigma_y}{303} = \frac{32.3}{95}
\]

\[\Delta \sigma_y = 103.02 \text{MPa}\]
Therefore new estimated yield strength of material in the centre zone:

\[ 303 - 103.02 = 199.98 \text{MPa} \]

This means that the applied load of 170MPa is 56% of \( \sigma_y \) (yield strength) of the weld material. Even though the same load was applied, the material experienced the loading differently as there is a hardness difference throughout the weld. FSW welded samples formed the basis of the analysis as the samples welded with the process have proved to have the best fatigue life when compared to fusion welding processes. The calculations have also proved that fatigue was carried out in the elastic loading range in all the samples tested.

Using hardness as a measure of strength not only gave the fatigue failure’s yield strength but a clear indication of where a sample could fail under tension. In welded samples this method could give a clear indication of yield as it was done on the cross section, which was where most irregularities in a weld were found.

5.4. FRACTOGRAPHY

5.4.1. Results and discussion

Fractography is part of material science that involves describing the topography of a separation surface formed during a breakage of material continuity (Warmuzek et al 2004). The same procedure was carried out on the fractured fatigue samples obtained from the three welding
processes as a means of determining crack initiation sites. Figure 5.10 shows a typical fracture surface obtained from a FSW welded specimen.

Figure 5.10: Fractured FSW sample and SEM images

The macrographs of a typical FSW fracture surface are shown in Figure 5.10(a) and (b). The lines on the fractured surface are a result of the cold rolling process of aluminium. Inclusions in the fast fracture region can be seen in Figure 5.10(c) as indicated by the circle.
The pores observed at Figure 5.11(a) and (b) can act as potential sites for crack initiation unlike the FSW welded plates; the fracture surface consists of weld metal with no traces of the parent material. The MIG-Laser hybrid welded joints had dendrites with fine precipitates of AlSi (AWS ER 4043) typical of microstructures resulting from the weld metal.

Macrographs of the fracture surface are shown in Figure 5.11 (a) and (b) while (c) shows the morphology of the internal surface of shrinkage porosity on the fracture surface. The fast fracture region exhibited microvoid coalescence (MVC) which is typical for a ductile overload type failure. The fatigue failure originated from one of the micro voids on the far right end of the fractured specimen in (b) shown by an arrow.
According to Lefebvre et al [2006] MIG welds present two predominant forms of porosity, interdendritic defects of the order of $10 - 50 \, \mu m$ in length and gas porosity of the order $50 - 200 \, \mu m$. The MLH process had gas porosity that was larger than $200 \, \mu m$ in diameter and there was variation in size of the gas porosity. All the gas porosity was found in the weld metal.

![Figure 5.12: Gas porosity inside and on the fracture surface](image)

Porosity is one of the problems prevalent in laser welding of aluminium alloys and this was shown by porosity at a depth of $9.78 \, \mu m$ from the surface in Figure 5.12 (a) and (b). Shown in (b) is the inside of gas porosity. According to Matsunawa et al, bubbles in laser welding are generated by intense evaporation of metal in the keyhole.

However, the most characteristic property in laser welding is the formation of large pores at the bottom or middle part of deeply penetrated welds. Such pores are frequently formed in the pulsed (PW) spot welds and continuous wave (CW) deep keyhole-type welds of alloys which contain volatile elements such as magnesium (Matsunawa, Katayama et al 1998).
Figure 5.13: A FSP fractured sample and SEM images

Figure 5.13 (a) and (b) show macrographs of the fracture surface of the FSP aluminium alloy 6082-T6 alloy plate. The fractograph in Figure 5.13 (c) shows an apparent partial forging defect in the fast fracture region. The MLH process is one of the best fusion welding processes available to weld aluminium but was compromised by the evaporation of magnesium which resulted in having pores in the microstructure as shown at Figure 5.13 (d) and (f). The void shown in the fractograph at Figure 5.13 (f) shows an internal discontinuity on the fractured surface and the effect of FSP becomes clear on the macrograph at (a) which shows contrasting macrostructure surfaces. The FSP process resulted in a refined microstructure free of voids and pores. This process resulted in an increase in the fatigue life of MLH welded samples but the percentage improvement could have been higher had it not been for the voids found in the microstructure.
5.5. MICROHARDNESS

5.5.1. Results and discussion

Sections were taken from FSW, FSP and MLH welded plates for micro-hardness testing. They were then mounted in polymeric resin and ground and polished following standard metallographic procedures. The temperatures attained during welding and the size of the welding tool played a significant role in the resulting mechanical properties (Fuller et al). Each welding method’s characteristics play a role in the final hardness properties of the weld. The results from hardness testing of the three processes have been combined in Figure 5.14 and show the hardness profiles of the three processes and the hardness of the parent material.

![Figure 5.14: Micro-hardness results [at 3mm from bottom surface]](image-url)
The FSW process showed the lowest hardness in the centre at 57.2% followed by the FSP process at 59.2% of the parent material's hardness at the weld nugget area which forms part of the TMAZ. In FSW welded heat treatable alloys like 6082-T6 there is a loss in strength in HAZ as shown by the graph in Figure 5.14, where the strengthening precipitates may dissolve or coarsen (Taban and Kaluc et al).

The weld metal has the lowest hardness and the base material the highest; the reason could be the differences in composition of the two materials, hence the varying hardness values. The MLH process had the highest hardness after the base material when compared to other processes at 73.6% of the parent material. In FSP and FSW welded aluminium alloy 6082-T6 specimens the hardness varied across the weld and there was a decrease in hardness across the welded joint.

With the FSW and FSP processes the minimum hardness occurred just outside the nugget area. The heat affected zone played a role in the ductility and strength of the weld area and this explained why the FSW process resulted in a more ductile weld area than that obtained with both FSP and MLH welding processes. An increase in hardness away from the centre indicated that some work hardening also occurred at the weld area in both FSP and MLH.
The reduction in hardness was caused by the breakdown of the delicate-age hardened microstructure that provided the original hardness, very common among heat treatable aluminium alloys [Kristensen & Slater et al]. This was not evident with the MLH welding process and this was a result of the filler material used in the welding process which behaved differently to the stirred parent material in FSW welding.

According to Kristensen and Slater due to the close relationship between hardness and strength, a hardness decrease is expected to be followed by a similar decrease in strength and in general this must be accounted for in the design phase. In the case of tested specimens this becomes true as the decrease in strength on the MLH welded specimens was at the centre of the weld and to be precise in the weld metal. All the fatigue and tensile failures started at the centre of the weld and the decrease in hardness was at the centre as well.

According to Von Strombeck et al [1999] when a joint is defect free, the tensile properties are only dependent on the microhardness. At areas with voids there is a tendency of having a decrease in microhardness and most failures initiated at the void. The above statement applies mostly to friction stir welded specimens which are defect-free and also pure friction stir processed specimens (without MLH). Processes like MLH result in porosity in the weld as a result of the evaporation of magnesium particles caused by high temperatures attained by the welding process.
5.6. MICROSTRUCTURE ANALYSIS

5.5.2. Results and discussion

Figure 5.15 shows the macrograph of an FSW weld obtained from using the FSW tool available at the MTRC. The FSW structure contains features not found in fusion welds, the reason being that, unlike fusion welding processes, no filler material is used and there is no groove preparation. The macrograph has no visible voids on the surface and the macro-sections show the characteristic features of an FSW welded joint.

![Figure 5.15: An FSW macrograph [Svensson et al]](image)

The joint is divided into a thermo-mechanically affected zone (TMAZ), the Heat Affected Zone and the Nugget area. The onion ring structure is also visible on the surface and there are no kissing bonds on the surface and the weld can be taken as defect free. The FSW process gives rise to noticeable microstructure changes. An optical micrograph reveals that deformation in the TMAZ results in severe bending of the grain structure. Figure 5.16 shows a typical FSW microstructure with refined grains in the structure.

![Figure 5.16: Optical micrograph of an FSW weld microstructure (in the nugget X100)](image)
Figure 5.17 shows a macrograph obtained from an MLH welded joint and its size depends entirely on the heat input into the joint. Upon visual inspection the top surface of the joint had v-shaped ripples which are characteristic of the MIG-Laser Hybrid process and no surface cracks were visible on the weld surface. The temperatures obtained during this process were much higher than those obtained in the other welding processes.

The high temperatures resulted in the distortion of the welded plates and also the heat input played a role on the final size of the seam appearance. The higher the heat input the bigger the seam, taking gap widths into consideration. The width of the weld joint varied in all the plates welded and there was no consistency in thickness of the weld joint, unlike in the FSW and FSP welding processes.

![Figure 5.17: The macrograph of a MLH welded joint](image)

Figure 5.17(a) shows the boundary between the parent material and the filler material and (b) consists of the whole weld structure. The joint has a dendritic structure which is formed mainly by the solidifying of the weld metal and the parent material.
Unlike the FSW process the shape of the seam depended upon the welding parameters used in the weld process. Fatigue strength was affected by defects formed as a result of the welding process and weld metal which were not apparent on the weld surface after the polishing of specimens. Owing to the nature of the fatigue testing process these defects initiated cracks which led to failure as most were closer to the surface inside the joint although unseen from the outside surface of the plate. The clear difference in the microstructure was due to the composition of the parent material (6082-T6) and the filler alloy (4043) and their different manufacturing processes.

Figure 5.18: Optical micrograph of the MIG-Laser Hybrid microstructure (x100)

Figure 5.18 shows optical micrographs of MLH welded aluminium alloy 6082-T6 as viewed on the cross section. The following regions; fusion zone, transition zone, heat affected zone and the parent plate, formed part of the micrograph. The fusion zone seen on the micrograph presents a fine dendritic structure in the central region, with equiaxed
dendritic structures whereas the edge of the fusion zone shows a more columnar structure.

With the FSW process, the stirring action refined the microstructure forming fine grain particles much smaller than those produced by the fusion processes. In heat-treatable alloys the weld zone became stronger partly because of the effect of heat treatment. Shown in Figure 5.19 is an FSP macrograph which shows three microstructural regions namely the fusion weld, the fine-grained FSP structure and the parent material respectively. The FSW welded side reveals characteristic features of an FSW welded microstructure which has a HAZ, the TMAZ and a nugget area. The most common feature of FSW welds, known as onion rings, can be seen on the FSP section of the macrograph.

![Figure 5.19: A macrograph of the FSP process](image)

The porosity caused by the MLH process was only removed on one half of the welded joint and the heat input introduced by the FSW process could not eliminate pores outside the reach of the FSP tool. There was a clear distinction between the two processes in that the FSP welded area
had a more refined microstructure which had an effect in improving the fatigue strength of the weld joint.

The introduction of FSP to MLH welds refined the microstructure and removed porosites only to a depth of 3mm and there is no clear distinct region separating the two welding processes on the macrograph. In Figure 5.20(b) is an optical micrograph which shows three zones in the FSP weld at higher magnification. The stirring action of the FSP tool results in high deformation and temperature during the welding process which results in fine recrystallized grains as shown in (a), finer than those of the parent material. The parent material grains show the typical elongated structure of rolled material.

![Image](image.jpg)

**Figure 5.20: Optical micrograph showing zones in an FSP structure (X100)**

The FSP process recrystallized the dendritic structure resulting in a fine microstructure. This agrees with the hypothesis which postulated that by introducing the FSP to an MLH weld, there would be an improvement in fatigue life of the weld. Shown in Figure 5.20(a) is part of the recrystallized dendritic microstructure formed as a result of the FSP process. A concentric ring could be seen formed as a result of the
stirring action of the FSP tool. Unlike with the FSW process the structure now contains a mixture of the filler material and the parent material.

Owing to the precision of the FSP process no defects were formed as a result of the process. The stirring action managed to recrystallize the microstructure to a finer structure than the base material.

5.7. SUMMARY

The tensile graphs generated showed a major difference from testing the parent material and those obtained from welded joints. The parent material had a higher tensile strength. Amongst the welded specimens the FSW process had the longest elongation followed by the FSP and MLH welded specimens respectively. The introduction of FSP to MLH welded Al-Mg-Si alloy plates increased elongation in the specimens while reducing the ultimate tensile strength.

The improvement in elongation was due to the repair of solidification porosity and also the change from a coarse grain to a fine grain microstructure. The FSW process had the highest elongation followed by the FSP and MLH processes respectively. Weld efficiency is the percentage ultimate tensile strength ratio of the welded samples to that of the parent plate. The MLH process had the best weld efficiency for the 0mm and 1mm gaps but lower weld efficiency for the 0.5mm gap due to speeds used to weld the gap.
The FSW process resulted in an increase in efficiency as the gap between the plates increased and had the best efficiency only for the 0.5mm gap. The weld efficiency of FSP specimens dropped as the gap between the plates increased - influenced by the speeds used in MLH welding of the 0.5mm gap. All the samples had more or less the same 0.2% proof stress value.
6.1. CONCLUSIONS

The purpose of this research was to study the influence Friction Stir Processing had on MIG-Laser Hybrid welded aluminium alloy 6082-T6 with varying gap tolerances. Mechanical and metallurgical properties of the welded joints were tested and analyzed. A modified tool based on the tool designed for FSW by Dr Calvin Blignault was designed, tested and used to perform friction stir processing on the MLH welds.

The shoulder design was based on the maximum width of the weld root bead formed as a result of the MIG-Laser Hybrid welding of aluminium alloy 6082-T6. Tool shoulder and pin ratios developed at TWI were used in determining the final pin diameter of the tool. The heat generated by the FSP tool was comparable and similar to that obtained by other researchers in the same field using different designs of friction stir processing tools. A combination of various speeds was used during the weld trials to determine the optimum speeds that could be used with the friction stir processing tool. All the welds developed with the new FSP tool were good based on the tensile results obtained in testing.
The speeds used during trial welding showed the influence of welding speeds on the final ultimate tensile strength of the material. The influence of the shoulder diameter on the heat dissipated by the shoulder was clarified with the aid of the tool temperature profile which showed the tool temperatures for both processes namely the FSW and FSP processes. The FSW tool has a bigger shoulder which explained the higher heat input generated by the tool compared to the FSP tool which generated less heat due to its smaller tool shoulder.

The FSP process was carried out successfully and the anticipated results obtained for the process. Although there was an increase in fatigue life it is believed that there could have been an improvement to the ultimate tensile strength and fatigue life of the FSP joints if a bigger shoulder was used for the FSP tool. This is based on the tensile and fatigue results obtained with the bigger FSW tool with a 25mm shoulder diameter. There was an improvement in the microstructure of the MLH welds and microvoids visible on the macrostructure were removed with the introduction of the FSP process. The dendritic structure formed by the melting of the weld metal was refined by the FSP tool.

The FSW process has proved to be the best welding process for welding aluminium alloys. The results obtained proved this point as the process fared better than the MLH process with a higher fatigue life. All the failures occurred outside the weld area and there was no evidence of defects in the welds.
The following conclusions could be drawn from the research:

• The fatigue life of MLH welded Al-Mg-Si alloy is improved by the introduction of the FSP process for the 0.5mm and 1mm gap specimens. The individual MLH welds had the lowest fatigue life when compared to FSP and FSW for all gaps evaluated;

• There was a significant reduction in hardness in the weld zone for the friction based processes (FSW and FSP) investigated. The MLH had the highest hardness after the base material when compared to the other processes;

• The tensile results obtained for the FSW process were lower than MLH welded joints for the Al-Mg-Si alloy used due to thermal softening. The FSP process resulted in reduction in tensile strength of MLH welded Al-Mg-Si alloy tested;

• In tensile testing the Al-Mg-Si alloy fractured in the heat affected zone (HAZ) for all FSW welded joint gaps. FSP and MLH fractured at the centre of the weld zone.

6.2. OBSERVATIONS

• The microstructure of MLH welded Al-Mg-Si alloy has been evaluated characterizing the variation in grain and coarse particle distribution. There is a dramatic change in the grain geometry between the weld metal, the HAZ and the base material;
SEM images of FSP specimens showed contrasting microstructure surfaces, one with a microstructure free of voids and pores and another half with voids and pores for FSP specimens;

- The MLH process is sensitive to changes in speeds and no two different gaps should be welded with the same welding speed. This is evident with the reduction in weld strength of the 0.5mm gap welded with the same speed used to weld a 0mm gap. FSW and FSP process had speeds tailored for each process and speeds are not related to the gaps welded.

6.3. FUTURE WORK

Research needs to be done in the area of FSP as it has proved to be a viable method that could be used to improve mechanical and metallurgical properties of various aluminium alloys. Aluminium alloys are normally grouped according to their applications in industry and the introduction of FSP tends to improve an otherwise good alloy by introducing super plastic properties and grain refinement of the parent material.

The research unveiled factors overlooked at the commencement of the project, which could further improve the applications and properties introduced by the FSP process. Future research in this field should include the following topics:
• An investigation into the effects of varying FSP tool shoulders on the mechanical and metallurgical properties of MLH Aluminium Alloy 6082-T6 joints;

• An investigation into the effects of varying FSP tool pin diameters and pin length on the mechanical and metallurgical properties of MLH Aluminium Alloy 6082-T6 joints;

• An investigation into the effects of temperature distribution introduced by FSP on the mechanical and metallurgical properties of MLH Aluminium Alloy 6082-T6 joints.
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APPENDIX A

TOOL
Cut Major RS
Draft angle -30
Deep 6mm

Groove radius 12mm

Major Ø14.05

Counterbore Ø 6 x 15 deep
Drill Ø 0.68

Cut Flat

A (2:1)

All fillets R0.5 unless otherwise specified
Surface roughness in the range of 1.6
APPENDIX B
TEMPERATURE PROFILES
Temperature Profile for FSP Weld 10.6 - Plate A1

Temperature Profile for FSP Weld 10.9 - Plate D2
Temperature Profile for FSW Weld 1.20

Temperature Profile for FSW Weld 1.13
APPENDIX C
TENSILE RESULTS
Tensile Results [FSP vs FSW vs MLH] - 0mm gap

Tensile Results [FSP vs FSW vs MLH] - 0.5mm gap
Tensile Results [FSP vs FSW vs MLH] - 1.0mm gap

Stress [MPa] vs Extension [mm]
APPENDIX D

FATIGUE RESULTS