Robotic Friction Stir Welding for Automotive and Aviation Applications

Jeroen De Backer  Bert Verheyden

May 2009
Robotic Friction Stir Welding for Automotive and Aviation Applications

Jeroen De Backer  Bert Verheyden

May 2009
Robotic Friction Stir Welding for Automotive and Aviation Applications

Jeroen De Backer 4ELAU
Bert Verheyden 4EMEM
SAAB Automobile AB & Volvo Aero Corporation

Abstract
Friction Stir Welding (FSW) is a new technology which joins materials by using frictional heat. In the first part of this thesis, a profound literature study is performed. The basic principles, the robotic implementation and possibilities to use FSW for high strength titanium alloys are examined. In the next phase, a FSW-tool is modelled and implemented on an industrial robot in a robot simulation program. Reachability tests are carried out on car body parts and jet engine parts. By using a simulation program with embedded collision detection, all possible welding locations are determined on the provided parts. Adaptations like a longer FSW-tool and a modified design are suggested in order to get a better reachability. In different case studies, the number of required robots and the reduction of weight and time are investigated and compared to the current spot welding process.

Description of the process
FSW is based on the heat generation between a rotating tool and two work pieces. Unlike most other welding methods, FSW joins materials in a plastic state instead of a liquid state. It obtains excellent mechanical properties. The major advantage is the possibility of joining dissimilar materials like aluminium and steel.

Simulation results
The robot simulation program Robcad has embedded collision detection. This toolbox allows to check the reachability for every desired welding location.

Conclusions
- The FSW tool is successfully implemented on an industrial robot using the Robcad software.
- Collision-free welding can be performed between the floor panel and the A-structure of the car.
- The floor panels are unreachable by performing a right-angled lap weld. This issue can be solved by edge welding the floor panel.
- Friction Stir Welding of inconel engine parts is successfully simulated.
- Design adaptations are suggested in order to get better and faster welding of both the car parts and the turbine parts.
- Lap welding between aluminium and steel is nearly impossible since the required heat in the steel would melt the underlying aluminium.

Acknowledgements
Special thanks to our supervisor Torbjörn Iller at University West and all the people who supported us during this thesis, in specific Tommy Christensen from Saab, Mats Jellingmark from Volvo Aero and Michael Solow from Lскаb for their help and for the interesting study visits, and to Anna-Karin Christiansson for helping us in Sweden. Also a word of thanks to our supervisor in Belgium, Philippe Gery, and to the international offices in Ghent and Trollhättan for giving us the opportunity to do our master thesis in one of the most advanced technology centres of Sweden.

Further information
Torbjörn Iller
Production Technology Centre
University West - West of Engineering Group
SE-501 80 Trollhättan, Sweden
Torbjorn.iller@hv.se

Jeroen De Backer
jeroen@fandav.be

Bert Verheyden
bert.verheyden@volvocar.com

Figure 1: Friction stir welding process.

Figure 2: FSW Robot

Figure 3: FSW Equipment

Figure 4: FSW of an inconel rear turbine structure.

Figure 5: Work cells for car body assembly.
Robotic Friction Stir Welding for Automotive and Aviation Applications

Abstract

Friction Stir Welding (FSW) is a new technology which joins materials by using frictional heat. In the first part of this thesis, a profound literature study is performed. The basic principles, the robotic implementation and possibilities to use FSW for high strength titanium alloys are examined. In the next phase, a FSW-tool is modelled and implemented on an industrial robot in a robot simulation program. Reachability tests are carried out on car body parts and jet engine parts. By using a simulation program with embedded collision detection, all possible welding locations are determined on the provided parts. Adaptations like a longer FSW-tool and a modified design are suggested in order to get a better reachability. In different case studies, the number of required robots and the reduction of weight and time are investigated and compared to the current spot welding process.

Keywords: Robotic, Friction Stir Welding, Simulation, Reachability
Preface

First of all, we’d like to say thanks to our international coordinators and the people from the international offices in Gent and Trollhättan for their effort in making a new International agreement between the two universities which enabled us to finish our master program at University West.

A great expression of gratitude to our supervisor, Mr. Torbjörn Ilar for his important contributions from time to time, to this thesis.

We also want to thank all the other people who supported us during this thesis, in specific to Tommy Christensen from Saab, Mathias Fremäng from Volvo Aero and Mikael Soron from ESAB for their help and the interesting study visits, and to Anna-Karin Christiansson for assisting us in Swedish.

Finally a special word of thanks to our parents: Paul and Lutgarde, Willy and Viviane for allowing us to study abroad and for guiding us for many years.

It was a great experience for us to work at PTC in a pleasant atmosphere…

Tack Igen!
Contents

Preface ..........................................................................................................................1

Contents .........................................................................................................................2

List of symbols and abbreviations ..................................................................................4

CHAPTER I Introduction .......................................................................................................5

I.1. Why this project? .........................................................................................................5

I.2. Input.............................................................................................................................5

I.2.1. Parts .........................................................................................................................5

I.2.2. Robot .........................................................................................................................6

I.3. Purpose .......................................................................................................................6

I.4. Organization of the thesis ............................................................................................7

CHAPTER II The FSW process ............................................................................................8

II.1. Introduction ................................................................................................................8

II.1.1. Evolution ................................................................................................................8

II.1.2. The FSW process ..................................................................................................8

II.1.3. Advantages and disadvantages .............................................................................10

II.2. Microstructure ..........................................................................................................11

II.3. Materials ....................................................................................................................12

II.3.1. Aluminium .............................................................................................................12

II.3.2. Titanium ................................................................................................................13

II.3.3. Lap Joint of aluminium and steel ........................................................................14

II.4. Process variants .........................................................................................................15

II.4.1. Stationary shoulder friction stir welding .............................................................15

II.4.2. Friction stir spot welding .....................................................................................16

II.5. Tool design ...............................................................................................................16

II.5.1. Summary ...............................................................................................................16

II.5.2. Different tool shapes ............................................................................................17

II.6. Defects and residual stresses ....................................................................................18

II.6.1. Defects ..................................................................................................................18

II.6.2. Residual stresses ..................................................................................................19

CHAPTER III Robotic FSW ...............................................................................................20

III.1. Introduction .............................................................................................................20

III.2. Robot design ............................................................................................................20

III.3. Controlling the system ............................................................................................21

III.4. Force control methods ............................................................................................21

III.4.1. Direct force control .............................................................................................21

III.4.2. Indirect force control ..........................................................................................22

III.5. Considerations regarding force control .................................................................23

III.6. Parameters ..............................................................................................................23

III.7. Path planning ..........................................................................................................24

III.8. Complex geometries ..............................................................................................24

CHAPTER IV Simulations ..................................................................................................25

IV.1. Introduction .............................................................................................................25

IV.2. Simulation set-up .....................................................................................................25

IV.3. Tested welds ..........................................................................................................26

IV.3.1. Steel floorpanel to steel A-structure with wheelhouses .....................................26
IV.3.2. Floorpanel to A-structure without wheelhouses..........................................26
IV.4. Floorpanel – Aluminium wheelhouses.............................................................28
IV.5. Untested simulations..........................................................................................30
IV.6. Suggestion for a FSW line..................................................................................30
IV.7. Construction of the jet engine parts.................................................................32
   IV.7.1. Introduction...............................................................................................32
   IV.7.2. Welding of the outer segment to the vane..............................................32
   IV.7.3. Joining the I-profiles................................................................................34
   IV.7.4. Assembly of the hub cone........................................................................34
   IV.7.5. Welding of the hub cone..........................................................................34
   IV.7.6. Welding of the front and rear cover rings.............................................35
IV.8. Conclusions........................................................................................................35

CHAPTER V Case studies...............................................................................................36
V.1. Weight saving with different metals.................................................................36
   V.1.1. Purpose.......................................................................................................36
   V.1.2. Methodology.............................................................................................36
   V.1.3. Conclusion.................................................................................................36
V.2. Weight saving by performing FSW.................................................................36
   V.2.1. Purpose.......................................................................................................36
   V.2.2. Methodology.............................................................................................37
   V.2.3. Conclusion.................................................................................................37
V.3. Comparable lead time.......................................................................................38
   V.3.1. Purpose.......................................................................................................38
   V.3.2. Number of robots......................................................................................38
   V.3.3. Maximum welding length..........................................................................40
   V.3.4. Conclusion.................................................................................................40
V.4. Dimension of the test cell at PTC.................................................................42
   V.4.1. Lay-out 1: Standard configuration.........................................................42
   V.4.2. Lay-out 2: Reformed base plate..............................................................43
   V.4.3. Lay-out 3: enlarge angle between fixtures.........................................43
   V.4.4. Lay-out 4: Replaced turntable.................................................................44
   V.4.5. Conclusion.................................................................................................44

CHAPTER VI Conclusions..........................................................................................45
VI.1. Conclusions........................................................................................................45
VI.2. Future work.......................................................................................................45

List of Figures..............................................................................................................47

References................................................................................................................48

Appendices
Appendix A: Datasheet ABB IRB 7600 .................................................................B:1
Appendix B: Properties of aluminium.................................................................B:2
Appendix C: Properties of titanium.................................................................B:3
## List of symbols and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSSW</td>
<td>Friction Stir Spot Welding</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction stir welding</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat affected zone</td>
</tr>
<tr>
<td>PTC</td>
<td>Production Technology Centre</td>
</tr>
<tr>
<td>SSFSW</td>
<td>Stationary shoulder friction stir welding</td>
</tr>
<tr>
<td>TCP</td>
<td>Tool Centre Point</td>
</tr>
<tr>
<td>TCPF</td>
<td>Tool Centre Point Frame</td>
</tr>
<tr>
<td>TMAZ</td>
<td>Thermo mechanically affected zone</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Solidus temperature</td>
</tr>
<tr>
<td>TWI</td>
<td>The Welding Institute</td>
</tr>
</tbody>
</table>
CHAPTER I Introduction

I.1. Why this project?

Since the invention of friction stir welding (further abbreviated as FSW) 18 years ago, it was obvious that this technique had some significant advantages regarding automotive and aviation industries. However, a breakthrough is never achieved so far. This is partially because FSW has to compete with some very common and reliable techniques like arc and spot welding. Also Saab uses spot welding very often. In general, a regular car contains between 2000 and 3000 spot welds. Due to the introduction of robotic FSW, the process gains in flexibility which makes it now attractive to explore the possibilities and limits for automotive applications. If it turns out that FSW is as fast and as flexible as spot welding, it can be considered to replace the spot welding installation by friction stir welding robots. Volvo Aero has also economical reasons to consider friction stir welding. For their production of engine parts, they often have to purchase very large parts in titanium and inconel with diameters up to 3.5m. Since only a few companies are able to fabricate those large parts, this has always been an expensive factor in the production chain. Friction stir welding allows Volvo Aero to produce these large parts itself. It will also allow smaller manufacturers to produce these big parts, what might cause a price drop for these products. Although this new welding technique still needs some further development for high strength materials, an own production is very realistic and can result into a more cost-efficient process.

I.2. Input

I.2.1. Parts

Following figures show the parts that need to be welded. The parts, provided by Saab are the rear floor panel (Figure 1) and the attached A-structure (Figure 2) and the wheel hoods (Figure 3). In the first figures are all the different parts shown separately, in (Figure 4) is the assembly of the three parts shown.

Figure 1. Floorpanel

Figure 2. A-structure
The model that needed to be simulated for Volvo Aero was a turbine rear structure as shown in (Figure 5). This figure shows the whole assembly, constructed of different parts. How these parts are assembled is explained in chapter IV.

I.2.2. Robot

The required robot was given at the start of this project. It is an ABB IRB 7600, chosen for his high payload. The 6th axis is removed, and a FSW tool was mounted on it. The datasheet of the robot is added in appendix A. The implemented FSW equipment is provided by ESAB.

I.3. Purpose

In general, the main purpose of this project is to detect the limitations of FSW and in particular the constraints of the robot. Since not all places are reachable in a good way with the robot, not every requested location is possible to weld with FSW. For Saab, the intention of this thesis is to provide information about which welding paths are feasible with the FSW-robot. With this information it should be possible for the
designers to create parts which are fully weldable with FSW, so that FSW can become part of the designers toolbox.
The main goal for Volvo Aero is gaining knowledge in how the given part can be assembled. This can be done in different ways, like explained in chapter IV. The intention of this thesis is to give an indication which of these options is the best.
A last goal is to provide all interested persons with a basic knowledge about the evolution of both the FSW process and the robotic implementation.

I.4. Organization of the thesis

This thesis is divided into six chapters with following content:

- Chapter 2: This chapter gives an overview of the topics related to the process. It starts with the evolution of FSW after which the underlying thought of this welding technique is explained. There’s also paid attention to the tool, the microstructure and a couple of process variants. Because this thesis is particularly for automotive and aviation industry, the section in which the weldability of different materials is described, handles the welding of Al and Ti.

- Chapter 3: The emphasis of this chapter lies on the implementation of a robotic system to FSW. The robot design is explained, as well as the differences between the two main different control systems, namely force control and position control.

- Chapter 4: Because one of the main purposes of the project was to simulate the welding of different parts, there is a chapter dedicated to it. In this chapter is shown which parts are able to weld and which parts aren’t due to collision. This chapter gives some indications about possible design adaptations.

- Chapter 5: In this chapter an answer is given to some practical questions, e.g. the number of robots that is needed, a quantitative weight comparison between an aluminium floor panel and one made of steel, etc.

- Chapter 6: This chapter contains the conclusions of the work done, it ends with some indications of possible future work.
CHAPTER II  The FSW process

II.1. Introduction

II.1.1. Evolution

Friction Stir Welding, later in the text abbreviated to FSW, was invented in December 1991 by Wayne Thomas at The Welding Institute (TWI) in Cambridge and was patented in Europe, USA, Japan and Australia. Since its invention was the potential of this relatively new welding technique widely recognized but a commercial breakthrough didn’t follow immediately. One of the reasons for this was the poor flexibility of the process. Since FSW uses large forces, the work piece must be clamped rigidly. Conventional machinery, such as milling machines, were modified to be used for friction stir welding. The major drawback of such FSW-machines is that they are only able to weld in a two-dimensional space. Consequently, FSW was mainly used for non-automotive applications, e.g. aviation fuel tanks, airplane wings, train roof- and side panels etc.

With the introduction of robotic FSW, the process gains in flexibility and one may suspect that FSW will also be commonly used in future automotive applications.

II.1.2. The FSW process

FSW uses a specific tool as shown in (Figure 6). It consists of a cylindrical shouldered tool with a threaded pin, also called probe (More details about the tool design are described in section II.5). The tool rotates while it is slowly plunged into the two materials, which are butted against each other, until the shoulder achieves a full contact with the two plates. This friction makes sure that the material heats up and softens. It’s important that the temperature does not exceed the melting temperature. The material needs to be plasticized, but not melted. A temperature of about 60 to 80 % of the melting temperature should be reached. Once this temperature is reached, the material in front of the tool will also be heated up a little bit, making it possible to start the traverse motion. This motion follows the seam, mostly with a slight angle called the tilt angle. The pin stirs in the material, which causes a material flow from the advancing side (the side where the rotational movement is in the same direction as the traverse movement) to the retreating side (Figure 7). The material is forged due to the intense contact between the shoulder and the material and a solid state is created. Once the traverse motion has reached his end-point the tool is retracted while it’s still rotating. This leaves a hole in the weld. There are two possibilities to solve this issue. The first is to use a retractable pin. With this kind of tool, the pin is automatically retracted into the shoulder at the end of the weld before the tool is pulled away from the weld seam. The second possibility is the use of run-on/run-off tabs. These are extensions of the parent material which are machined off after welding.
Basically, the FSW process can be divided in 4 different phases:

- **Plunge**: In the plunge, the tool penetrates slowly into the material with a predefined rotation speed until the shoulder has a full contact with the material. The required forces are the biggest in this phase.

- **Dwell**: In this phase the material is being heated up. There is no traverse motion and the dwelling phase ends when the material has reached a satisfying plasticity. In thin material this phase can be very short or can even be neglected.

- **Weld**: After reaching an adequate temperature, the tool moves in the direction of the weld seam with a certain tilt angle and traverse speed.

- **Retract**: After reaching the end-point the tool is pulled away from the material while it is still rotating. This leaves a keyhole in the material.

The previous figure explains FSW for a butt joint, but also other kind of joints are possible. (Figure 8) gives an overview of the possible joint geometries.
II.1.3. Advantages and disadvantages

The main advantage of FSW is that it’s a solid state process, this means that it takes place below the melting temperature of both materials. Because of this, it is now possible to weld two materials with a different melting temperature. Other important benefits of the process are:

- Possibility to weld overhead: Since there is no filler material used, gravity has no influence.
- Lower weight: Working without filler material means that the total weight of the weld will be lower comparing to welding with filler material. This is very beneficial in car and aerospace industry because a lower weight means a lower fuel consumption and less emissions.
- Possibility to weld materials which are considered as difficult to weld, e.g. 2xxx and 7xxx aluminium alloys.
- Low distortion.
- Good mechanical properties.
- No arc, fume, porosity nor spatter.
- Low shrinkage.
- No final processing required, e.g. cutting off slag.
- Good fatigue life.
- Good weld quality.
- Reduced number of parameters: There are in fact only 5 parameters considered in FSW applications (i.e. down force, rotation speed, travel speed, plunge depth and tilt angle) which is much less than other processes like MIG or Plasma welding.
Because of these advantages, Smith describes FSW as a lean, mean and green process (Smith, 2004).

The two main drawbacks are currently:

- The work pieces must be clamped rigidly. This often requires a backing bar.
- FSW leaves a keyhole at the end.

**II.2. Microstructure**

The microstructure of a FSW weld depends on a few aspects like rotational and traverse speed, the pressure, the material and the tool design. This makes it difficult to describe the microstructure in general. However, following scheme was developed by TWI and is accepted by the Friction Stir Welding Licensees Association. It divides the cross-section in four parts (Figure 9).

![Figure 9. Microstructure](image)

- **A:** Unaffected material: This is the region on a distance from the weld centre. It’s the region that is not affected by the generated heat. Although the material might have experienced a thermal cycle, it is not affected by this cycle. This means that the microstructure and the mechanical properties aren’t changed. It’s often referred to as ‘parent material’.
- **B:** Heat-affected zone (HAZ): This is a region a bit closer to the weld centre. This has certainly experienced a thermal cycle and the mechanical properties and/or the microstructure are modified by it but it doesn’t show any plastic deformation. In the HAZ the changes in properties are comparable to those in the HAZ for other thermal processes. The shape of the HAZ is typically trapezoidal, as can be seen in Figure 9.
- **C:** Thermo mechanically affected zone (TMAZ): This region has a change in microstructure and/or mechanical properties. But in contrast to the HAZ, the TMAZ has a plastic deformation. The grain size is similar to the grain size in the parent material.
- **D:** Weld nugget: This is the part of the TMAZ that has been recrystallized. The grain sizes in this weld nugget are smaller than the grain sizes in the parent material. According to Murr et al. (Murr, 1998) the grain size in this zone is 10 times smaller than in the parent material, which has a beneficial effect on the mechanical properties, e.g. fatigue strength. The shape of the weld nugget can vary, depending on the material that needs to be welded and the parameters. According to Bradley and James (Bradley, 2000) the diameter of this weld nugget is slightly greater than the diameter of the FSW tool, but significantly smaller than the shoulder diameter.
However, it needs to be said that the above-mentioned classification is typical for aluminium, but it could be different for other materials. In steel, for example, there is no weld nugget, but the TMAZ is completely recrystallized instead. Sometimes there are concentric rings visible in the draw-section as shown in (Figure 10). These rings, sometimes called “onion rings”, are situated in the centre of the weld nugget. There are a few theories about those rings: Some authors share the opinion that these rings are a result of the threaded tool, as cited by Bradley and James in (Bradley, 2000). These rings are considered as an indication of a good quality of the weld. In contrast to the latter theory, Larsson et al. (Larsson, 1998) assume that the rings are not a result of the different grain sizes, but rather a result of a variation in orientation of these grains.

![Figure 10. Onion rings](image)

However, both researches have shown that the rings are not visible in all alloys and that it’s more difficult to see them when the traverse speed and/or the rotational speed increases.

**II.3. Materials**

FSW makes it possible to weld different materials such as aluminium, steel, magnesium, copper, zinc, titanium, nickel and in particular, a combination of these materials such as aluminium with steel.

In this project the emphasis lies on automotive and aerospace industries, so in following passages a short review is given on friction stir welding of Al and Ti, the two most commonly used materials in these applications.

Section II.3.1 is a summary of the work done in (Soron, 2007) and handles about the welding of different Al-series.

Section II.3.2 is a short overview of the work done in (Russell, 2006) and (Russell, 2007). These articles handle about the welding of titanium alloys.

**II.3.1. Aluminium**

Different kinds of aluminium were welded in a lap joint and tested visually. The equipment that was used was an ABB IRB7600-500 with a FSW tool mounted on its 6th axis. The results for AA6xxx-AA5xxxx (both commonly used in automotive applications) and AA2xxx-AA7xxx (both commonly used in aerospace industry) are summarized briefly in this paragraph.

AA6063-T6: It’s well known that this material is weldable with fusion welding techniques and certainly with FSW. While testing, there were no problems with welding thin materials.
The weld had a good quality when welding with a rotational speed around 2500-3000 rpm and an axial force of 3000N.

AA6082-T6: This has the highest strength of all AA6xxx-series. It has a good corrosion resistance. The same rotational speed was used, but in order to create a good weld, the axial force was increased with 40% to 4200N.

AA5754: This has a very good corrosion resistance, especially in seawater. This makes it an often used material for ship building applications. A weld with good quality was achieved with 1500 rpm (a little bit lower than in the 6xxx-series) and an axial force around 5500N (a little bit higher than in the 6xxx-series).

AA5xxx/Diecast: In this test, a sheet of wrought aluminium was welded on a sheet of cast aluminium. This is seen as a typically setup for FSW, since this technique is able to join different materials. The problem that raised there was controlling the plunging operation. When going first into a soft material and afterwards in a harder material made the plunging motion unpredictable. Nevertheless, the weld was carried out. But to achieve a good weld, an axial force of 13000 N was needed.

AA2024-T6: This is a high strength alloy and is commonly used in aircraft industry. For this test there was a specially designed tool used with a scrolled shoulder. Because of the hardness of this material, attention needed to be paid while plunging. Normally, the axial force during the plunging phase is approximately 1.25 times the axial force while welding. In this case, however, the force while plunging was twice the force while welding. A good weld was achieved with a rotational speed of 850 rpm.

AA7075: In this alloy, zinc and copper are added to provide high strength. Because of this, it's difficult to weld with fusion welding techniques. There were 2 sets of parameters used (one for plunging, one for welding) like for all high-strength alloys. A weld with good quality was achieved.

AA7020-T6: This is another high-strength aluminium alloy that was shown weldable with FSW. The main problem with this is the small interval in parameters for obtaining a good quality.

II.3.2. Titanium

Welding titanium has always been a challenging topic due to the properties of the material, e.g. hardness. Because of this hardness, the wear is much higher comparing to welding aluminium. Also the temperature is higher: titanium has a melting temperature around 1660° C while aluminium has a melting temperature around 660° C. Having in mind that the temperature should be around 60-80% of the melting temperature (Chao, 2003), the temperature of the material should be approximately 1000-1300° C. This puts high demands on the tool material: not only should it be able to stand the higher temperature, it should also be inert to titanium on higher temperature. Tests have shown that the regular tools (the ones used for welding aluminium) are just inadequate. Therefore TWI has done research to other materials such as high temperature metals, ceramics and refractory alloys. Tests have shown that the refractory alloys, such as Tungsten-based alloys, are the most suitable materials. In 1995, TWI has welded a 6mm thick Ti-6Al-4V plate. In a later study they welded a 5mm thick Grade 2 Commercially Pure titanium. The microstructure of this weld shows a mix of transformed and non-transformed material. This is an indication that some zones in the weld (but not all) were heated above the beta transus temperature, which is for Ti approximately 900° C.

One of the difficulties in welding titanium is to control the heat input. The heat input is determined by the feed ratio and the rotational speed. A low feed ratio and a high rotational
speed will cause a high heat input and vice versa. Both a too high and a too low heat input cause problems regarding quality: A too cold weld causes a poor root, while a too hot weld causes a poor surface. When welding titanium, however, the interval of combinations in both parameters is rather small in order to get a good weld. This makes it difficult to control the process. The reason of this problem is the thermal conductivity. When we take a closer look to the FSW of aluminium, we see that the friction causes heat. This heat has an effect on the zone in front of the welding tool. Due to the thermal conductivity, this zone also heats a little bit and pre-softens. Because of this, the resistance decreases which makes the traverse motion easier. However, the thermal conductivity of titanium is rather low so the material in front of the tool doesn’t pre-soften much and maintains a high resistance. Research to other materials, process variants, etc. has been going on and a better technique was invented in 2004-2005, named stationary shoulder friction stir welding (SSFSW).

II.3.3. Lap Joint of aluminium and steel

For the rear part of the Saab model, a floor panel can be made of both aluminium or steel. In both cases, the issue of dissimilar material welding arises. There are many tests carried out for butt welds between aluminium and steel but when it comes to lap welds, which is the case in this project, very few studies have been reported. In tests by (Elrefaey, 2005), satisfying results are presented for a lap weld from aluminium to steel with rotation speeds of 1500rpm and travel speeds of 5mm/s. The influence of the pin depth turned out to be very important for a good weld quality. Another important factor here is the direction. In the previously mentioned article, the two materials are successfully welded from the aluminium side. In the quest for articles regarding lap welding between dissimilar materials, no scientific reports were found that illustrate the impossibility to weld steel to aluminium from steel side. However, all the simulated welds in this report are carried out from aluminium side and the assumption is made that the inverse direction is not possible because of the following considerations:

- The temperature required to soften the steel would melt the aluminium and will cause the weld to collapse.
- As molten aluminium attacks all metals, this will damage the clamping system and the tool.
- Most probably, there would be intermetallic formations (FeAl, Fe₃Al etc.) which would make the welds very brittle.
- The FSW tool will suffer much more when it’s plunged directly into the steel, rather than plunge it into aluminium and realising a combination between mechanical interlocking and metallic bonding.

These arguments are based on intuition, rather than real experiments. It could be interesting to see that assertion confirmed in further research work.
II.4. Process variants

II.4.1. Stationary shoulder friction stir welding

As stated in section II.3.2, welding titanium has always been a difficult matter. TWI has done some research on other possible materials and process variants to make this easier. In 2004-2005 they invented a new welding technique, namely stationary shoulder friction stir welding (SSFSW).

This technique uses a rotating pin, a non-rotating shoulder and an inert gas to protect the welding region. (Figure 11) shows the welding head of a SSFSW machine.

![SSFSW head](image)

Figure 11. SSFSW head

1. Rotating spindle
2. Draw bar
3. Tool holder
4. Water cooling jackets
5. Inert gas input
6. Support bearing
7. Tool head (stationary)
8. Workpiece
9. Sliding shoe
10. Backing plate
11. Sliding seal
12. Tool pin (rotating)
13. Cooling gas tubes
14. Gas chamber
15. Inert gas input

Due to the stationary shoulder, there is no surface overheating and the heat is focussed around the pin. This results in a uniform temperature distribution, which is often seen as beneficial. Some advantages of SSFSW are:

- A reduced thermal cycle
- A smaller heat affected zone
- A smooth surface
- Easier to control the heat input

In the initial stadium of development, good welds were made on a 6.35mm thick Ti-6Al-4V with traverse speed between 60-80mm/min and rotation speeds of 400-500rpm. Recent tests have already demonstrated welding speeds of 200mm/min.
II.4.2. Friction stir spot welding

Another variation of the process is friction stir spot welding (FSSW). This is a combination of FSW and resistance spot welding. This means that it uses a rotating tool like in FSW, but there is no linear motion in the direction of the weld seam. The tool rotates against the upper plate and penetrates into both materials. This causes a plastic material flow in 2 directions: the axial and the rotary direction. When the tool is retracted it leaves a hole and the materials are welded to each other. The tool is exactly the same as the FSW tool: a convex shoulder with a threaded pin.

FSSW can be split up in two major variants: The first with a single sided tool, the second uses a double sided tool. This double sided tool is a C-frame, which can be seen in (Figure 12). The main advantage of this is the reduced force because the bottom of the C-frame works as a backing plate. This is the reason why there is less power needed comparing to friction stir welding.

There are, however, a few differences comparing to FSW. First of all, the configuration: FSW is mostly used for materials which are butted against each other while FSSW is used for welds with a lap joint geometry. A second difference is the temperature. As stated earlier is the ideal temperature for FSW between 0.6 and 0.8 T\textsuperscript{s}. For FSSW is this temperature slightly higher. In tests made by Gerlich in (Gerlich, 2005) was this temperature 0.94 T\textsuperscript{s} for Al-6111. When testing the welds in a destructive way, the failure of the weld depends on its quality. A good weld, i.e. a weld with few defects, has a high shear strength and is ductile and will fail by a tear-out. When the weld is of a poor quality it will fail in a more brittle manner at the weld nugget.

II.5. Tool design

II.5.1. Summary

The design of the tool affects a couple of different important parameters like heat generation, material flow, the forces needed in the process and the uniformity of the welded
joint. This means that using an adequate tool is a very influential parameter. Concerning the
design of the tool, there are two important aspects, namely the radius and the surface shape.
According to Deqing (Deqing, 2004) there is a correlation between the radius of the
shoulder and the radius of the pin, i.e. a 3 to 1 ratio. This means that the radius of the
shoulder is three times the radius of the pin. Dubourg (Dubourg, 2006) state that the
diameter of the shoulder is related to the thickness of the plate:
\[ d_{\text{shoulder}} = 2.26 \times t_{\text{sheet}} + 6.99 \]
These two statements claim that once the thickness of the plate is known, the diameter of
both the pin and the shoulder are not longer free to choose, in order to achieve a good
weld. The length of the pin is always a little bit shorter than the material that needs to be
welded. The shoulder produces most of the heat, but the material flow is determined by
both the shoulder as the pin.
The material used for the FSW tool depends on the application. When welding soft
materials, e.g. aluminium, heat treated steel is sufficient enough. This makes it possible to
make a FSW tool with a low cost. For welding materials with a higher melting temperature,
e.g. Ti, the wear is significantly greater than for welding materials with low melting point.
Hence, tools made of heat treated steel are simply inadequate and tungsten-based alloys or
polycrystalline cubic boron nitride (PCBN) are used instead. Prater (Prater, 2007) proposed
to use a diamond coated molybdenum tool. This reduces the wear and reduces also the axial
force. Due to the thread and the rotation the material experiences a vertical force which
needs to be downwards to have a good material flow. This makes the turning direction not
free to choose.

**II.5.2. Different tool shapes**

TWI has developed several FSW tools, each with his own design (see Figure 13). The
Whorl™ and MX triflute™ have both tapered threads. This causes a vertical velocity
component which is beneficial for the material flow. Even though they can be used for butt
joints, they can’t be used for lap joints. For this, TWI developed the Flared triflute™ and A-
skew™. The Flared triflute™ is similar to the MX triflute™ but has an expanded flute. The
A-skew™ is a tapered threaded tool. Its axis is inclined to that of the machine spindle. The
two latter tools have an increased swept volume relative to the volume of the pin. Because
of this, the stir region is bigger which causes a wider weld. This makes it feasible to create
a decent lap joint. Because of the rotation and the translation, there is an asymmetry in
material flow and heating across the pin. For this a new tool is designed, called Re-stir™.
This tool changes rotating direction every 180°. When a thick plate needs to be welded and
it’s impossible to weld it in one run, a bobbin tool (Figure 14) could be the solution. With
this tool its possible to weld both sides at the same time (Eriksson, 2001). The benefits of
this tool are:

- No backing bar require
- Reduced welding time (1 run instead of 2)
- Reduced vertical forces
II.6. Defects and residual stresses

II.6.1. Defects

The two most common defects are porosities and surface defects. These defects are often the result of bad welding parameters. Using a constant rotational speed and increasing the travel speed for example, can cause a wormhole to initiate at the bottom of the weld. The size of such a wormhole can increase with increasing travel speed because of the inadequate downwards material flow. An important parameter is the travel speed to rotational speed ratio: A high travel speed comparing to rotational speed tends to favour the formation of wormhole defects. Another important parameter is the heat input. Heterogeneity in heat generation can lead to defect formation, i.e. surface overheating can cause excess flash.

Elangovan et al. (Elangovan, 2007) investigated the correlation between rotational speed, tool pin design and defect formation. They’ve examined five different pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square). The result of this research showed that a squared pin had the least defect formation. This because the flat faces of the pin causes a pulsating action and this causes a more effective stirring.
II.6.2. Residual stresses

Residual stresses affect the distortion behaviour. Compressive stresses aren’t always harmful. On the contrary, sometimes they are even beneficial since the compressive character of the stress will prevent an initial defect to grow. Tensile stresses, however, “help” the initial defect to grow. This can cause crack initiation which can lead to a fatal failure.

Residual stresses can be measured in two ways: in a non-destructive manner or in a destructive manner. The destructive way is by drilling a hole. The non-destructive way uses x-rays or a neutron source.

The research done by Peel et al. showed that the longitudinal stress increased with increasing traverse speed. This because of the steeper thermal gradients and the reduced time for stress-relaxation (Peel, 2003). A second thing noticed is that traverse stresses don’t directly depend on the rotation speed. It’s also shown that the weld region is under tension and the workpiece is under compression.

There are two things, related to residual stress, typical for FSW. The first is the existence of an additional stress due to the rotational and translational motion of the tool. The second is the effect of stirring: Stirring can relieve some stresses in the TMAZ.
CHAPTER III Robotic FSW

III.1. Introduction

The knowledge and applications of the FSW process, as mentioned in the previous chapter are increasing fast. However, implementing this on specially designed, high cost machinery has one major drawback: the process is not flexible. Every adaption in the process requires an adaption of the “hardware”, the FSW machine. The use of an industrial robot for FSW could be a major improvement because many process changes can be intercepted by a software adaption. Since the first industrial robots had insufficient stiffness and since they couldn’t deliver the required downforce, they were not suitable to use for FSW. Nowadays, there are robots with very high payloads of one thousand kilograms and more which are also very stiff. This makes a breakthrough of robotic FSW possible. In this chapter, the focus will be on the existing solutions for robotic implementation of this new welding technique.

There are two different robot concepts useful for FSW. A parallel and a serial construction. Even though a parallel construction is much more stiff and provides very good results as shown in (Von Strombeck, 2000), it has a few important drawbacks. The system is more complex, has a very limited workspace and the cost, compared to a serial robot with the same payload, is much higher. Nevertheless the compliance problems are very detrimental in a serial design robot, this design is more interesting for applications in the automobile industry and will therefore be discussed in this chapter.

III.2. Robot design

A FSW-tool is not a part of the standard robot “option-list” yet. Only very few welding companies offer a FSW-robot. The basic design of this robot is explained in this paragraph. The sixth axis of the robot allows the TCPF to turn around the z-axis of this frame. But since the tool of the FSW equipment has the same rotation, the last robot-axis becomes redundant and can be removed. For the process in general, high rotational speeds and high torques are required so a powerful motor is needed. Different solutions were presented for this issue. The motor can be either hydraulic or electric. The major advantage of an hydraulic motor is a lower volume to power ratio as demonstrated in (Smith, 2000). In these experiments, successful welds could only be performed in a very limited workspace in front of the robot and when the z-axis of the TCP didn’t deviate much from the vertical axis. The limited success here was mainly caused by a too long distance between the TCP and the last robot link, the wrist.

Another possibility is the use of an electromotor. For a successful plunge operation, it is found that the motor should be able to provide a torque of at least 60 Nm (Schmidt, 2005), which is not feasible with a small motor inside the wrist. However, the motor can be placed outside the wrist. Furthermore can the motor of the 6th axis be removed and replaced by the gearbox of the FSW equipment. These two changes allow that the TCP is located much
closer to the 5th link which results in less compliance issues, lower torque and good welding results in a predefined workspace as demonstrated in (Soron, 2007).
When it comes to friction stir spot welding, the increasing forces are no longer an issue since they are located in the FSW equipment itself and not in the robot joints.
The physical force sensing is not a problem. New force sensors can measure unidirectional forces up to 80kN and torques up to 6kNm with resolutions up to 160N and 3Nm respectively (ATI Catalogue, 2008). In this case, the precision is a more important factor than the maximal torque.

III.3. Controlling the system

A robot in general applications moves in the free air and is subject to rather small forces. It uses position control to keep the TCP on the correct path. When it comes to robotic FSW, there arise huge forces in the joints of the robot which result in compliance problems. Therefore, a new control strategy is implemented namely “force control”. This new approach greatly improves the welding quality.
When the real path differs from the planned path using position control, the robot will try to follow the planned path, no matter how. As shown in (Figure 15), the tool tries to follow the path A-B, but since the surface doesn’t fit with the predefined path, the robot forces will increase in C until the maximum joint values are reached. The result is often unstable robot behaviour and thus a bad welding quality. If the robot has force control in the direction normal to the surface, the tool will be slightly lifted between C and B and the force will be kept stable on a predefined value.

III.4. Force control methods

Between the end effector and the last robot axis, a force- and torque sensor is implemented. There are several approaches to handle these measured variables. Generally, they are divided into 2 categories namely:

III.4.1. Direct force control

This includes all the force control strategies that generate directly the actuation signal, computing the force error function using usually a PID controller. The user can set the desired force value. The main advantage is the good result combined with the simplicity:
there is no need for a more sophisticated controller if the results of the PID controller are satisfactory.

**III.4.2. Indirect force control**

This strategy uses an external force loop to generate position commands to an internal loop, constituted by a position based force controller. The external force loop (with force sensor feedback) generates the position reference for the internal loop (with position encoder feedback), using an admittance relation. This relation is often represented as a second order mass-spring-damper system. This strategy was introduced for practical reasons: current manipulator control systems have built-in position controllers that don’t allow direct access to the joint motor torques.

The most adopted technique to use force control is a hybrid approach. This means that force control is applied in the z-direction, normal to the surface. The x- and y-direction are controlled by position control. The robot can thus never ‘know’ where its TCP is located since the location in the z-direction is defined by the measured force. When the tool moves
to the first welding position, it moves in the free air and force control is obviously disabled. At the beginning of the welding operation, the pin must be plunged into the material as mentioned in the previous chapter. For this operation, force control is necessary for good welding results so there should be a switch from position (in free air) to force control (during the plunge). This is a difficult part because as soon as force control is turned on, the pin tend to crash into the material. This problem can be resolved by turning on force control when the pin is very close to the work piece and –in case of direct force control- by increasing the desired force value. This means that a very small force is applied while switching from motion to force control until contact with the work piece is made, and increasing until the necessary plunging force is reached. When the tool moves along the path, for example in x-direction, deviations in the y-direction arise as well, due to force differences between the advancing and retreating side of the tool. An extra control element can be implemented as shown in (Soron, 2007) where these deviations are corrected by a linear estimation, based on previous measurements.

III.5. Considerations regarding force control

Force control is based on keeping a constant pressure in the z-direction while moving in the xy-plane. During the welding, there is a heat flow away from the actual welding point. This implies that the material in the next welding point is warmer and accordingly softer (Nandan, 2008). Often, the applied force must therefore be reduced along the path. In cases where the work piece is small, with a smooth surface and a rather simple welding geometry, it can be recommended to use only position control since the connection between temperature and required force is hard to define. It could be useful to investigate the relation between a measured temperature and the necessary force.

III.6. Parameters

Comparing to traditional welding processes like Arc- and TIG-welding, the number of parameters can be remarkably reduced. There is no gas flow, no current and no wire supply and (mostly) no water flow. The most important parameters for this type of robotic friction stir welding are:

- rotational speed (rpm)
- travel speed
- normal force
- lateral force
- tool attitude (tilt angle)
- shoulder plunge
- penetration ligament (butt joints)
- penetration into the bottom member (lap joints)

There are in fact only 5 parameters considered in robotic FSW applications (i.e. down force, rotational speed, travel speed, plunge depth and tilt angle). It’s clear that there are less parameters which can cause problems in FSW comparing to MIG welding with ca. 13
parameters, TIG welding with ca. 15 or plasma welding with the impressive number of around 24 parameters. Fewer parameters implies fewer problems what results in higher repeatability and faster project switching. As mentioned earlier, the lateral forces are not considered in robotic FSW. When the robot would weld with lateral force control, it can never have any idea about where his TCP is located in the workspace.

**III.7. Path planning**

The most frequently applied approach nowadays is the offline programming with robot software. For commonly used applications like spot welding, there are toolboxes in CAD software to simulate the optimal collision free path. Unfortunately, those toolboxes are not available for FSW (yet) so the paths in these simulations are user defined, in every single location. It is not possible to generate a path, based on robot poses instead of locations. This means that the program itself defines the joint configuration and that it does not consider any collision along this path. It’s up to the user, to choose intermediate locations that avoid these collisions. The next chapter of this thesis will be based on offline programming using Siemens Tecnomatix® Robcad.

**III.8. Complex geometries**

One main reason to choose a robot instead of the ‘classical FSW machinery’ is the great flexibility. This also includes the ability to weld complex paths in a multidimensional workspace instead of just a planar workspace. The current FSW robots are able to weld almost every type of curve in a horizontal plane. Welding in the vertical plane requires some more effort since the robot joints are more forced into their maximal deflections. An application of 3D paths is demonstrated in (Soron, 2007) where the robot follows a curve in the yz-plane. However, this is not ‘real 3D’ since the x-position stays constant along the path. When it comes to full 3D welding, only very few -if even existing- successful operations are demonstrated so far.
CHAPTER IV Simulations

IV.1. Introduction

The main goal of this thesis is a reachability test for car body parts from Saab. These simulations are discussed in the following paragraphs. Moreover, construction tests for jet engine parts from Volvo Aero are carried out and discussed in the last paragraph of this chapter. Due to the absence of a FSW robot in our research centre, the work was reduced to computer simulations. In the following paragraphs, the term “successful welding” implies that a path could be generated with realistic welding positions and without collisions. This does not mean that a practical test was carried out, nor that the suggested welding path is the optimal regarding time and weld quality. This chapter contains a lot of pictures to illustrate the resulting configurations.

IV.2. Simulation set-up

The robot (ABB IRB 7600-500) is imported from the ABB website directly in the Robcad “.co” format. The whole 6th link is removed, together with the redundant 6th axis. The FSW equipment is created by ESAB and imported in Robcad using the iges-format (Figure 18). The body parts from Saab are created in the Unigraphics environment. To convert these files to Robcad, the best results are achieved by using the Robface-format. It should be mentioned that the iges-format does not generate smooth surfaces and contains gaps up to 1mm between adjacent surfaces when imported in Robcad. This is detrimental for several reasons. First of all, the imported file is seen as a ‘group of unclosed surfaces’ instead of a solid, which disables all the Robcad-tools that make use of solid bodies. Furthermore, a collision between the part and the tool can not be detected on the locations where a ‘virtual gap’ exist. The last disadvantage is of course the visual aspect: in both print-outs and recorded videos are these gaps visible, which doesn’t look very attractive.

Figure 18. FSW robot
IV.3. **Tested welds**

IV.3.1. **Steel floorpanel to steel A-structure with wheelhouses**

When the wheelhouses are welded to the floorpanel, before the A-structure and floorpanel are joined, a lot of accessibility problems arise, especially the motors of the 5th axis and the FSW-motor are colliding with the wheelhouses. The obvious suggestion is here to have the welding of the floor panel to the A-structure as a first operation in the system and to add the wheelhouses in a following stage of the process.

IV.3.2. **Floorpanel to A-structure without wheelhouses**

IV.3.2.1. **Simulation results**

In this simulation, the rear part of the floorpanel is welded to the A-structure. The floorpanel can be made of both aluminium and steel since the welding is carried out from floorpanel side anyway. The welding is performed along the flanges of the A-structure (Figure 19). Since the surface is rather big, one robot will most likely have compliance problems when trying to reach the whole surface. The solution is suggested to use two separate workcells, containing two robots on both sides of the part. The whole weld is divided amongst these four robots (Figure 20 and Figure 21). They can weld the floorpanel to the A-structure successfully but with a lot of different plunge operations and consequently a lot of retraction holes. The required time, based on previous test results, is calculated in the next chapter of this thesis.

![Figure 19. A-structure with marked flanges](image-url)
Figure 21. Welding path on floorpanel (rear)

**IV.3.2.2. Improvements**

During the simulation, the tool must be lifted very often, due to irregularities in the welding path as shown in (Figure 22). These ‘bumps’ are reinforcements and provide more strength in the bottom plate. A reduction of these bumps gives a smooth welding path, which will give better and faster welding results but will –most probably- reduce the stiffness of the floorpanel. It should be considered in further design modifications to avoid or replace these reinforcements.
IV.4. Floorpanel - Aluminium wheelhouses

IV.4.1.1. Simulation results

The wheels are covered by the so called wheelhouses. These aluminium parts are welded to the floorpanel and this connection must be waterproof, preventing the water circulations around the wheels to enter the car. Considering the third paragraph regarding lap welding from steel side, these welds are done from the outer side, starting from the aluminium wheelhouses. It is impossible to reach the weld locations when the parts are in the same orientation as in the previous workcell. The part is therefore turned 180° around the x-axis and lifted until the weld is approximately 1700mm above the robot base (Figure 23). In this configuration, the full path is still unreachable in one time. Two FSW robots weld the left and right –unidentical– wheelhouses in four different pieces, with each piece leaving a retraction (Figure 24).  

Figure 22. Reinforcements interrupting the welding path
IV.4.1.2. Improvements

The suggested paths above will probably be sufficient regarding strength but since the welding path consists of 4 different pieces, this is not the optimal solution for a good sealing.

In another set-up, a turn- and tilt table is introduced where the part is tilted stepwise from 45° to 90° (Figure 25). Furthermore, the pin is stepwise enlarged from 20 to 40mm. These two modifications give encouraging results. The full path can be reached in one step without lifting the tool when a tilt angle of 60° and a pin length of 30mm is used. This also means that only one retraction hole is present.
IV.5. Untested simulations

The previous simulations include obviously not every possible configuration. Some of them are impossible to reach for several reasons:

- Welding from the steel A-structure to the steel floor panel:
The U-formed structure makes it impossible to reach the flange with the standard FSW robot. The tool must be increased in length with at least 20mm to reach the flange and the front side of the floorpanel will not be reachable in every case. Only a larger flange could give a solution. Considering the assumption in paragraph II.3.3., this is not possible with an aluminium floorpanel anyway. The only advantage would be, that the parts are in the same orientation (180° turned) as in the third cell where the wheelhouses are added.

- Welding the wheelhouses from the inner side:
The wheelhouses can be welded to an aluminium floorpanel from the inner side of the car. However, due to the robot design, there can never be welded perpendicular to the surface. One option is oblique welding on the edge of the A-structure but this is an inconvenient position for FSW and can lead to a bad welding quality. In case of a steel floor panel, the impossibility of steel-to-aluminium welding arises again.

IV.6. Suggestion for a FSW line

The aim of this simulation chapter is in first place to check the reachability on different parts, but it could be useful to give a main concept of how the FSW line at Saab could look like. The designed line in (Figure 26) consist of different elements:

- Supply units for the floorpanel, A-structure and wheelhouses provide the different parts to the different workcells.
- Fixtures in each workcell should intercept the high forces with FSW and provide sufficient support below the welding paths
- Pick-and-place robots put the parts from the supply unit on the correct fixture
• Six FSW robots, divided over 3 cells weld the 4 parts together.
• An transport facility between different cells should be included when the parts are not placed with a robot from one cell to another.

Figure 26. Concept of a FSW line for Saab
IV.7. **Construction of the jet engine parts**

### IV.7.1. Introduction

Volvo Aero provided a model from a turbine rear structure for this thesis. The issue here is not a time-effectiveness problem as at Saab, but also the reachability gives some problems in these simulations. The aim is to investigate how all the subparts can be assembled logically to a complete structure by using a friction stir welding robot. These parts are made of inconel, a nickel-chromium-based alloy. This material is good oxidation and corrosion resistant. It retains strength over a wide temperature range and therefore well suited for service in extreme environments such as jet engines.

The basic idea to assemble this part is by starting from 6 different subparts as shown in (Figure 27). The next paragraphs can be seen as an instruction how these subparts must be assembled one by one in a way which is considered optimal by the authors of this thesis. Also here should be mentioned that no strength tests are carried out on this assembly.

![Figure 27. Rear turbine structure with labelled subparts](image)

### IV.7.2. Welding of the outer segment to the vane

The first suggestion to weld these parts is with a T-weld. Therefore, the vane is rigidly clamped on the sides and the bottom. This fixture should surround the vane completely to make sure the part does not fold or bend when applying the required force for FSW.

The outer ring segment is placed on the fixture and T-welded from the segment through the vane. This set-up with a possible clamping mechanism is shown in (Figure 28). The vane is a narrow part of approximately 4mm thick. The feasibility of this T-weld is very
doubtful because of the limited thickness of the vane. There are different possibilities which could make this weld successful:

- One possibility to improve the welding quality is by increasing the thickness at the top and the bottom of the vane with at least a few millimetres.
- An alternative could be a corner fillet weld from the inside but the results of a corner weld with FSW are very poor. Other welding techniques such as laser welding are probably more suitable here.
- The last option is by adding a flange to the vanes. This will make both the clamping and the welding much easier and is –from FSW point of view- the best solution.

**IV.7.2.1. Welding of the inner segment to the vane**

The welded piece remains clamped, is turned and the inner segment is also T-welded to the Vane, with the same considerations as above. These operations are performed for each vane and result in 13 profiles, further called I-shaped profiles (Figure 29).
IV.7.3. Joining the I-profiles

First of all, these profiles are clamped on another fixture. Two adjacent outer ring segments are welded together, turned and than the inner segments are welded in the same way. Every simulation in this thesis is performed with the FSW robot from ESAB. In (Figure 30) is demonstrated that the full part can not be welded as a whole due to collisions of the actual FSW equipment with the part. The only way to reach the inner ring is a smaller motor in the FSW equipment or a redesign of this equipment.

![Figure 30. Colliding FSW equipment](image)

IV.7.4. Assembly of the hub cone

Unlike the inner and outer rings, the hub cone is purchased as a whole part. It is welded inside the inner ring segment. One way to assemble these parts is by sliding the whole inner ring around the hub cone. Since the tolerances are very small, a temperature manipulation (i.e. crimping the cone) could give a solution. Another way is to use 2 half “segment rings” which are placed around the cone and welded afterwards. The problem here is that these half rings can’t be completely welded together.

IV.7.5. Welding of the hub cone

As mentioned earlier, a corner fillet weld is hard to perform with FSW (Figure 31), especially in hard materials like inconel. Therefore, a design modification is suggested. When the toolframe of the robot is increased up to 40mm and a flange is added to the cone, it is possible to weld these parts. A perfect lap weld is impossible because welding perpendicular to the inner segment causes the robot to collide. The suggestion is made, to add a flange as in (Figure 32) where the tool penetrates the first part perpendicular (generating sufficient heat at the shoulder) and the second part under an angle of 60°.
IV.7.6. Welding of the front and rear cover rings

These rings are in one piece and can be butt welded to the outer ring segment by turning the full part 360° while the robot is locked. Sufficient support underneath the outer segments is required since they are only a few millimetres thick.

IV.8. Conclusions

The floorpanel, the A-structure and the wheelhouses from Saab can be joined together in three different workcell, consisting of 2 two robots. The first two cells weld the front and rear part of the provided floorpanel to the A-structure. The actual floorpanel contains many reinforcements on the welding path which causes the tool to lift very often and introduces many retraction holes. A decrease of these reinforcements will decrease the number of holes accordingly. The wheelhouses are welded to the floorpanel in a third workcell. The robot has difficulties to reach the whole welding path. If the tool is extended one centimetre and the part is tilted, the robot has a full reachability. However, welding this complex path is very hard for the robot.

Welding the rear turbine structure from Volvo Aero faces some important constraints when it comes to robotic FSW. The narrow vanes makes a T-weld almost impossible. The robot with FSW equipment is also very large what makes perpendicular welding of the complete inner ring impossible. However, this does not mean that FSW is not a suitable technique for the assembly of the rear turbine structure. A modified robot design or the use of fixed FSW machinery instead of a robot make the major part of this assembly possible to weld.
CHAPTER V Case studies

V.1. Weight saving with different metals

V.1.1. Purpose

The weight of a car and a plane is a very important fact. It’s widely known that a heavier car consumes more fuel and emits more CO$_2$. Therefore, weight reduction is one of the most important research topics in transportation industry nowadays. Considering the density, one can conclude that the density of aluminium is much lower than the density of steel (2.7 g/cm$^3$ comparing to 7.8 g/cm$^3$). However, aluminium is not as strong as steel so a thicker plate is needed. The thickness of the floorpanel should be 0.7mm in steel and 1.2mm in aluminium for having the same strength. When comparing the density ratio and thickness ratio of aluminium to steel, which is 0.35 and 1.72 respectively, one can conclude that the use of aluminium in a car can decrease its weight. In this case study, this impact is numerically investigated for the floorpanel.

V.1.2. Methodology

The volume of the floor panel is given by Saab, this is $2.17351 \times 10^6$ mm$^3$. It needs to be said that this is the volume of the given rear floorpanel (see chapter I, Figure 1) and not of the whole floorpanel. The car consists of three different floorpanels. With this volume, the surface area of the plate can be determined. This will be the same for the aluminium plate, so the volume of the aluminium plate can be calculated by multiplying this surface area by the thickness. Multiplying this volume by the density of the materials gives the weight in both cases. The numerical completion is shown in table 5.1.

<table>
<thead>
<tr>
<th></th>
<th>Surface area [mm$^2$] =Volume/0.07</th>
<th>Volume [mm$^3$] =Surface area*thickness</th>
<th>Weight [kg] =Volume*density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>3105014.286</td>
<td>2173510</td>
<td>16.953</td>
</tr>
<tr>
<td>Aluminium</td>
<td>3105014.286</td>
<td>3726017.143</td>
<td>10.060</td>
</tr>
</tbody>
</table>

Table 5.1 Weight comparison Al-steel for rear floorpanel

V.1.3. Conclusion

The latter calculation shows that using aluminium instead of steel will reduce the weight of the rear floorpanel from 16.953kg to 10.060kg, this is a reduction of 6.893kg. This means that, relatively seen, the weight in aluminium is 59.3% of the weight in steel.

V.2. Weight saving by performing FSW

V.2.1. Purpose

Since there is no material added and the heat affection is limited with FSW, it is obvious to investigate more possible weight savings. The present body parts are designed for spot
welding. This means that the flange of the A-structure has the required dimension for this technique. These dimensions are most likely different for other welding techniques. If the flange can be smaller for FSW than it is for spot welding, the weight of the car will be reduced. In these tests, welding should be performed with decreasing flange width until the smallest flange with acceptable welding results is reached. A numerical calculation is performed to get a relation between the weight and the flange width of the A-structure.

V.2.2. Methodology

First thing of all, the length of the flange is measured. The A-structure is shown in (Chapter IV, Figure 19) with the indication of the flange in black. This A-structure is made of steel. When calculating with a density of 7.8 g/cm³ and a thickness of 0.7mm, it is possible to determine the difference in weight when adapting the flange width. The length of the flange is measured using the point-to-point distance in Robcad’s measurement tools. These measurements resulted in a total distance of 5776mm.

Let’s recall the equation, set up by Dubourg:

\[ d_{\text{shoulder}} = 2.26 \cdot t_{\text{sheet}} + 6.99 \]

This equation is only valid for a butt joint configuration and not for a lap joint configuration. However, in order to get an idea of the order of magnitude, the calculations in this paragraph are done with the above mentioned equation.

Knowing the thickness of the steel plate, 0.7mm, the calculated diameter of the shoulder is 8.572mm. Looking back to (Chapter II, figure 9), one can conclude that the unaffected material starts at a diameter approximately twice the shoulder diameter which is in this case 17mm. The actual flange width – for spot welding – is approximately 20mm, depending on the exact location. This means that the flange can be shortened up to 3mm. In table 5.2 are these results translated in the corresponding weight.

<table>
<thead>
<tr>
<th>Change in width [mm]</th>
<th>Thickness [mm]</th>
<th>Length [mm]</th>
<th>Volume [cm³]</th>
<th>Density [g/cm³]</th>
<th>Change in weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7</td>
<td>5776</td>
<td>4.043</td>
<td>7.8</td>
<td>31.54</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>5776</td>
<td>8.086</td>
<td>7.8</td>
<td>63.07</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>5776</td>
<td>12.130</td>
<td>7.8</td>
<td>94.61</td>
</tr>
</tbody>
</table>

Table 5.2: Weight saving

V.2.3. Conclusion

This calculation shows that reducing the dimensions of the flange has only a negligible effect on the total weight of the car. Reducing the width with 3mm, reduces the weight of the car with only 95g.

In order to get here a reasonable weight reduction of let’s say 1kg is, a reduction of the surface area with 183150mm² is required. When this is the goal for the given A-structure, the width of the flange should be shortened with 38mm, which is of course impossible because the width is only 20mm.
V.3. Comparable lead time

V.3.1. Purpose

A full transition from spot welding to friction stir welding for the bottom structure at Saab is only realistic if a comparable lead time can be achieved. If the required time is much higher, this provides no economical benefit. At the moment, the involved spot welding robots need 2.2 seconds per spot weld and they perform a spot weld every 40mm. This means that the lead time for the given part can easily be calculated if the total seam length is known. This is calculated in the same way as in the previous paragraph, which results in 7976mm. This implies 200 spot welds in the whole assembly. With 2.2 seconds per spot weld, the lead time will be 440 seconds. The aim is to get the same or even a lower lead time with the friction stir welding installation.

In order to reduce the lead time, there are two possibilities. Initially, the number of robots can be increased. The second option is to reduce the total welding length. Spot welding doesn’t weld the whole seam either so intermittent welding could offer a solution.

V.3.2. Number of robots

First, the total length of the welding path of the whole assembly is calculated. This length is not the same as the 7976mm with spot welding because not all places are weldable and so the robot moves with a different speed in those places. This is solved by measuring the length that the robot is really welding. This gave a welding length of 4901.9mm. This means in fact that only 61.5% of the total seam length is welded. The distance that the robot moves from one point to another is also calculated, this is 27034mm if the return to the home position is included.

A second parameter is the welding speed. Further tests should show what the maximum welding speed is with good results for this specific application. Since these tests were impossible in this project, the further calculations are based on work by Elrefaey et al. where the welding of aluminium to steel in a lap joint configuration with comparable thicknesses is investigated (Elrefaey, 2005). They achieved good results using a rotational speed of 25 s⁻¹, this is 1500 rpm, and a welding speed of 5 mm/s.

A third parameter is the penetration time and the dwell time. Since the plate is very thin, the dwell time is negligible and the penetration time will be rather small. For these different process phases (penetration, dwell and retraction), a total time of 2 seconds per weld is taken.

It’s impossible to weld the whole part with one robot because of the robot’s compliance. This means that at least two robots are required, one on each side of the part. Also the length of the floorpanels is a problem which results in a further subdivision of the front and the back part.

To get the lengths of each of these the subdivisions, the created paths in chapter IV are recalled (Figure 33 and Figure 34).
Table 5.3 shows the different welding subdivisions with the welding length, the length in the air and the number of welds—which equals the number of penetrations— for each robot. Each path in the table has both a left and a right robot.

<table>
<thead>
<tr>
<th>Path</th>
<th>Welding length [mm]</th>
<th>Moving length [mm]</th>
<th>Number of welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floorpanel front</td>
<td>1269.6</td>
<td>5159.4</td>
<td>7</td>
</tr>
<tr>
<td>Floorpanel back</td>
<td>687.9</td>
<td>7000</td>
<td>10</td>
</tr>
<tr>
<td>Wheel hoods</td>
<td>509.3 (R)</td>
<td>2714.8 (R)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>477.6 (L)</td>
<td>2423.5 (L)</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>2466.8</td>
<td>14874.2</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 5.3: Lengths of the paths for one side

After these calculations, the required time for each phase can be determined.

- **Welding**
  
  A distance of 2466.8mm with a welding speed of 5mm/s requires 493.4 seconds.

- **Penetrating, dwelling and retracting**
  
  These phases are rather short comparing to the welding itself because of the thin plates. The time of these three actions will be approximately 2 seconds per segment. This means that there are 42 seconds required for the full process.

- **Moving from one position to another**
  
  To be able to calculate this, the speed of the robot has to be known. This is a tough issue and can only be determined with an advanced speed model or by measuring. To get a rough estimate of this time, an average speed is calculated, based on the datasheet of the ABB
7600 robot (Appendix A). The most evident choice is by calculating with the maximal TCP speed, mentioned in the ABB datasheet. However, this maximal speed is at the outer limits of the robot, while FSW is mostly performed, close to the baseframe. Therefore, the assumption is made, that the speed of the toolframe by moving from one position to another position is mainly realized by the first three axes. Thus an average speed can be calculated. The average maximum speed of the first three axes is 60°/s. Looking to the dimensions, one can conclude that the TCP is at an average distance around 1500mm. The speed of this TCP is thus:

\[ 60 \times \frac{2\pi}{360} \times 1500 = 1570.8 \text{mm/s} \]

Moving 14874.2mm with a speed of 1570.8mm/s requires 9.5 seconds. Once again, these calculations are based on the maximum speed of each joint so the real time will take certainly longer than this since there is an acceleration and a delay when approaching the workpiece. Considering this, this time is raised to 15 seconds.

These three times lead to a total time of 544.9 seconds with two robots, which is more than the aim of 440 seconds with spot welding. This means that it is impossible to weld the whole path in one cell with two robots. The number of robots that is needed can be estimated by:

\[ \frac{2 \times 544.9}{440} = 2.48 \]

If only the time factor is considered, this means that three robots should be sufficient to achieve the desired process time. Chapter IV illustrated that more robots are required in practice, due to access problems.

**V.3.3. Maximum welding length**

The previous paragraph has shown the impossibility of welding the whole length in a time less than the aimed 440 seconds with only two robots. This can be solved by more workcells or by intermittent welding. In that case, only a part of the total path is welded. In this paragraph is investigated how many percent of the total seam should be welded in order to achieve the desired lead time with two robots. This depends on a few parameters like welding speed, robot speed and dwell-, penetration- and retraction time.

There are two simplifications made, in order to make the calculation a bit easier. In the first is assumed that the number of welds is proportional to the welding length. This implies that all the welds have the same length. Although this is not completely correct, it will give a good approximation. The relation between the number of welds and the welding length is than

\[ f_1(x) = 0.00851x \]

with \( f_1(x) \) the number of welds and \( x \) the welding length in mm.

The second assumption is that the sum of the welding length and the moving length of the robot stays constant. This to assure that when the robot welds less, he moves more in the air without welding. The relation between this moving length and the welding length is:

\[ f_2(x) = 17341 - x \]
The relation between the total process time and the welding length is set up with a welding speed of 5mm/s, a penetration-, dwell- and retraction time of 2 seconds per weld and a robot speed of 1000mm/s. The relation is then:

\[ f(x) = \frac{x}{5} + 2 \times 0.00851 \times \frac{17341 - x}{1000} \]

The graph of this function is shown in (Figure 35). On the x-axis is the welding length visualized (in mm), and on the y-axis the process time (in seconds). This process time needs to be 440 seconds. In this figure can be seen that this implies a welding length a little bit less than 2000m.

Solving the equation \( f(x) = 440 \) analytically returns a welding length of 1957mm. This is 79% of the total welding length and 49% of the whole seam length.

**V.3.4. Conclusion**

There are two possibilities to make sure that the whole FSW-process is as fast as spot welding is nowadays. The first method is by raising the number of robots. Three robots are sufficient to obtain the desired lead time of 440 seconds. However, this odd number can entail compliance problems since one robot has to weld then on the other side of the part. So, two welding cells with two robots in each cell can be a better solution.

The second solution is intermittent welding. When using two robots and welding 49% of the whole seam, the lead time will be the same as it is with spot welding. However, it could be interesting to investigate how many percent of the weld seam is required to get the same strength as with spot welding. Spot welding welds once every 40mm, so there will be definitely some possibilities to reduce the welding length. When this is less than the calculated 49%, the lead time can further decreased. Based on observations of the spot welding process, one could say that this process welds less than 20% of the whole length, which means that there are good possibilities to reduce the total FSW length.
V.4. Dimension of the test cell at PTC

In the near future, friction stir welding tests will be carried out at PTC with the FSW robot from ESAB. A part of that project consist of the verification of the simulation results of this thesis, i.e. the reachability of different car and engine parts. For this, a robot cell will be constructed containing the robot with robot controller, 2 fixture tables and 1 turntable. The fixture tables used in these different lay-outs are 1.5m x 1.3m x 0.75m. Furthermore, there is some additional space for a desk and a desk chair inside the cell. This paragraph gives a short overview of different lay-out possibilities.

The main factor consideration in the cell design is the range of the robot since the minimum and maximum reach of the robot determine the distance of the fixtures relative to the robot. According to the datasheet of the robot, the minimum and maximum reach are 1128 and 2550 respectively. These values don’t take into account that the FSW-tool mostly points downwards. The real values will thus differ a little from these theoretical values. These real values are measured in Robcad by manually jogging the robot with the FSW-tool vertical. This gives 950 as minimum distance and 2300 as maximum distance on the floor. At the height of the fixture tables are these dimensions 1040mm and 2250mm respectively.

In the following paragraphs, some visualisations of the different lay-outs are shown. Each time, the green and red circle indicate the inner and outer reach. The fixture tables and the turntable are placed in such a way, that the whole table is reachable with the robot. Around the tables is enough place (at least 1m) to allow the user to mount the work pieces and to pass. Another choice, besides the position of the tables, is the position of the robot controller: Inside or outside the cell. Since it’s most common to place the robot controller outside the cell, this is done in each lay-out. Every cell has 2 doors, which ensure a good accessibility to each fixture, and has a solid base plate for mounting the robot, fixtures and turntable. This plate is indicated in black on the following designs.

V.4.1. Lay-out 1: Standard configuration

In this cell the turntable and fixtures are placed 90° relative to each other. The area enclosed by the fencing is 37.44m² (7.2m x 5.2m). The base plate has the dimensions: 5.75m x 3.2m (18.4m²). The isometric view and top view of this cell is shown in (Figure 36 and Figure 37).

![Figure 36. Lay-out 1: Isometric view](image)

![Figure 37. Lay-out 1: Top view](image)
**V.4.2. Lay-out 2: Reformed base plate**

In (Figure 37) is shown that both the left and right under corner of the base plate are not used. One can spare base plate material by using a lay-out as shown in (Figure 38 and Figure 39). In this lay-out there is only base plate material where it is necessary, i.e. under the robot, turntable and fixtures. Now, the base plate takes in a floor area of 12.325m². The total area of the work cell remains 37.44m². The smaller base plate is the main advantage of this lay-out. However, the more complex shape of this panel will probably induce a higher production cost.

![Figure 38. Lay-out 2: Isometric view](image1)

![Figure 39. Lay-out 2: Top view](image2)

**V.4.3. Lay-out 3: enlarge angle between fixtures**

Now the tables and fixtures are placed 120° relative to each other (Figure 40 and Figure 41). Because of this, the enclosed area will be slightly bigger. Comparing to the first lay-out, the total area increases with 7.2m² to 44.64m² (7.2m x 6.2m). The base plate is now 24.66m² (5.58m x 4.42m). This kind of positioning creates more space between the fixtures, which can be seen as beneficial when working with big work pieces.

![Figure 40. Lay-out 3: Isometric view](image3)

![Figure 41. Lay-out 3: Top view](image4)
**V.4.4. Lay-out 4: Replaced turntable**

In this final lay-out the turntable and fixtures are still 90° relative to each other, like in lay-out 1, but the turntable is turned 90° relative to its former position as demonstrated in (Figure 42) and (Figure 43). The enclosed area is equal to the area in lay-out 1, namely 37.44m², but the base plate can be reduced with 0.4m² to 18m² (4.45m x 4.05m). The main advantage of the first lay-out is the access to a more complex workspace. Assuming that the rotation around the first robot axis is very limited, means that the second and third robot axis are perpendicular to the first turntable axis in layout 1 and parallel with the first turntable axis in lay-out 4. This suggests that the first design gains more in flexibility.

![Figure 42. Lay-out 4: Isometric view](image1)

![Figure 43. Lay-out 4: Top view](image2)

**V.4.5. Conclusion**

Making a choice between different lay-outs will always imply thinking about different aspects like space, production cost, etc. Regarding the four proposed lay-outs, one can conclude that the first lay-out is better than the fourth lay-out because of the flexibility. In the third lay-out, there is a some more space between the fixtures but it requires much more space in the production hall. The available space in lay-out 1 and 2 should be sufficient to mount the work pieces which implies that lay-out 3 is not the best choice. Finally, one can conclude that the optimal cell design is lay-out 1 or lay-out 2, depending on the production and transportation cost of the base plate.
CHAPTER VI Conclusions

VI.1. Conclusions

This master thesis has given an introduction to robotic friction stir welding for people at University West, Saab Automobile and Volvo Aero who are interested in further development of this relatively new and promising welding technique.

In the first chapter, the whole FSW process was discussed briefly with focus on the possible materials and configurations, the different tool shapes and some process variants like stationary shoulder FSW. In the past, the development of FSW was mostly towards aluminium welding, since very few other welding techniques gave good results for this material, but more and more research work has shown that FSW is also suitable for high-strength materials like titanium and inconel.

The number of FSW applications, compared to other techniques, is still rather limited but one may claim that it becomes more and more in a so-called “state of the art”. The robotic implementation on the other hand, is still “state of the research”. The second chapter has indicated the advantages of this robotic implementation i.e. the high flexibility and the excellent results by using force control methods instead of pure position control.

The results of this thesis for Saab Automobile are quite promising. The A-structure of the car, the floorpanel and the wheelhouses were successfully joined in Robcad and a suggestion of how the complete FSW-workcell for these parts could look like was designed. Furthermore, design modifications are suggested to get a smooth welding path and fewer retraction holes in the part.

Some benefits of FSW are no extra material addition, a very restricted warming-up of the parts and high strength weld. These points make it very interesting for Volvo Aero to do some experiments with FSW. The provided rear turbine structure was simulated in Robcad. A stepwise assembly with the robot was composed, being aware of important constraints such as the design of the robot versus the size of the part, the limited thickness of the vanes and the necessity of full-length welding of the segments. It was shown that one of these factors must be adapted to allow the assembly of this product with the FSW robot.

VI.2. Future work

While simulating the models and performing different case studies, some interesting questions showed up. Due to the absence of a FSW robot, it was impossible to investigate these issues in this thesis work. Further research in FSW could give an answer to the following cases:

- Required effective welding length

In this project is calculated how long the weld can be, in order to have the same process time as spot welding. However, it’s possible that this gives a much higher strength than spot welding. A possibility to further decrease the lead time of FSW is by testing which percentage of the path needs to be welded to get the same strength as with spot welding. If
it turns out that less than 49% (this is calculated in paragraph V.3) of the seam needs to be welded to achieve a desired strength, the lead time will decrease.

- Temperature control

In chapter III is mentioned that failed welding operations along the path can be caused by the warming of the material. The work piece gets softer and the pin tends to sink in the material if the force set point remains constant. There could be a relation set up between the surface temperature and the necessary force, which might avoid the problem of sinking.

- Lap welding from steel to aluminium

In the simulations is assumed that lap welding with a penetration through the steel into the aluminium is impossible. This assumption was based on intuition, rather than scientific results. Further research work could confirm this statement.

- Reachability tests

In this project is the reachability tested with a robot simulation program. This doesn’t say anything about the applied forces. It is possible that positions which are pointed out as feasible (in terms of reachability of the robot) turns out to be infeasible in terms of compliance of the robot. This must definitely be tested in reality.

- Robot modification

While simulating both the Saab and Volvo Aero parts, it was clear that the size of the FSW equipment and the robot itself is a serious constraint to the reachability of certain locations. A reduction of these outer dimensions - e.g. by replacing the motor – will certainly have a positive influence on the access to the welding paths.
List of Figures

1. Floorpanel
2. A-structure
3. Wheel hoods
4. Assembly
5. Turbine rear structure
6. FSW tool (Soron, 2007)
7. FSW process - Copyright © 2008 TWI Ltd
8. Possible joint geometries - Copyright © 2008 TWI Ltd
9. Microstructure - Copyright © 2000 TWI Ltd
10. Onion rings (Dalle Donne, 1998)
11. SSFSW head – Copyright © 2006, TWI ltd.
12. C-frame – Copyright © 2007, Friction Stir Link
14. Bobbin tool – Copyright © 2007 Konspekt Kraków, Poland
15. Problem with pure position control
16. Direct force control scheme
17. Indirect force control scheme
18. FSW robot
19. A-structure with marked flanges
20. Welding path on floorpanel (front)
21. Welding path on floorpanel (rear)
22. Reinforcements interrupting the welding path
23. Workcell for FSW of the wheelhouses in turned and shifted position
24. Left wheelhouse, welded in 4 pieces.
25. Set-up with tilted configuration
26. Rear turbine structure with labelled subparts
27. Fixture for welding the vane to the outer rear segment
28. I-shaped profile
29. Colliding FSW equipment
30. Corner fillet welding of the hub cone
31. Modified hub cone
32. Welding of the wheelhouses
33. Indication of the welds
34. Plot of f(x)
35. Lay-out 1: Isometric view
36. Lay-out 1: Top view
37. Lay-out 2: Isometric view
38. Lay-out 2: Top view
39. Lay-out 3: Isometric view
40. Lay-out 3: Top view
41. Lay-out 4: Isometric view
42. Lay-out 4: Top view
References


Appendix A: Datasheet ABB IRB 7600

TECHNICAL DATA, IRB 7600 POWER ROBOT

SPECIFICATION

<table>
<thead>
<tr>
<th>Robot versions</th>
<th>Reach</th>
<th>Handling capacity</th>
<th>Center of gravity</th>
<th>Max. wrist torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRB 7600-500</td>
<td>2.55 m</td>
<td>500 kg</td>
<td>360 mm</td>
<td>3010 Nm</td>
</tr>
<tr>
<td>IRB 7600-400</td>
<td>2.55 m</td>
<td>400 kg</td>
<td>512 mm</td>
<td>3010 Nm</td>
</tr>
<tr>
<td>IRB 7600-300</td>
<td>2.8 m</td>
<td>340 kg</td>
<td>360 mm</td>
<td>2750 Nm</td>
</tr>
<tr>
<td>IRB 7600-250</td>
<td>3.1 m</td>
<td>225 kg</td>
<td>360 mm</td>
<td>2630 Nm</td>
</tr>
<tr>
<td>IRB 7600-150</td>
<td>3.5 m</td>
<td>150 kg</td>
<td>360 mm</td>
<td>1800 Nm</td>
</tr>
<tr>
<td>(IRB 7600-150I loaded with 100 kg)</td>
<td>1000 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Extra loads can be mounted on all variants.

50 kg on upper arm and 550 kg on frame of axis 1.

Number of axes: 6

PERFORMANCE

Axis working range

Axe 1 Rotation: +180° to −180°
Axe 2 Arm: +90° to −90°
Axe 3 Arm: +90° to −90°
Axe 4 Wrist: +180° to −180°
Axe 5 Bend: +100° to −100°
Axe 6 Turn: +300° to −300°

Axis max speed

225/500 kg/s: 240 kg/s: 150 kg/s
Axe 1: 750°/s: 750°/s: 750°/s: 100°/s
Axe 2: 20°/s: 60°/s: 20°/s: 60°/s
Axe 3: 55°/s: 80°/s: 80°/s: 80°/s
Axe 4: 100°/s: 100°/s: 100°/s: 100°/s
Axe 5: 100°/s: 100°/s: 100°/s: 100°/s
Axe 6: 100°/s: 100°/s: 100°/s: 100°/s

A supervision function prevents overheating in applications with intensive and frequent movements.

WORKING RANGE

IRB 7600-335/3.1
IRB 7600-400/2.55 / IRB 7600-500/2.55
IRB 7600-340/2.6
IRB 7600-150/3.5

ELECTRICAL CONNECTIONS

Supply voltage: 200-600 V, 50/60 Hz

PHYSICAL

Dimensions robot base: 1200.5 x 781 mm
Weight: 2400 ± 400 kg

ENVIRONMENT

Ambient temperature for mechanical unit
During operation: −35°C (-3.1°F) up to +50°C (122°F)
During transportation & storage: −25°C (-13°F) up to +55°C (131°F)
for short periods (max. 24 h) up to +70°C (158°F)

Relative humidity: Max. 95%

Degree of protection: IP07

Manipulator: Foundry
Controller: Air cooled
Computer system: Totally enclosed

Noise level: Max. 73 dB (A)

Safety: Double circuits with supervision, emergency stops

EMISSION: EMC/EMI shielded

Data and dimensions may be changed without notice.
Appendix B: Properties of aluminium

### Table B.1: Properties of Al

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>13</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>$26.98 , \frac{g}{mol}$</td>
</tr>
<tr>
<td>Density</td>
<td>$7.2 , \frac{kg}{dm^3}$</td>
</tr>
<tr>
<td>Modulus of Young</td>
<td>$72000 , \frac{N}{mm^2}$</td>
</tr>
<tr>
<td>Tensile stress</td>
<td>$40…100 , \frac{N}{mm^2}$</td>
</tr>
<tr>
<td>Hardness</td>
<td>$15…25 , HB$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.34</td>
</tr>
<tr>
<td>Coefficient of linear expansion (0-100° C)</td>
<td>$23.9*10^{-6} , K^{-1}$</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$0.899 , \frac{kJ}{kg.K}$</td>
</tr>
<tr>
<td>Melting point</td>
<td>$660° , C$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$238 , \frac{W}{m.K}$</td>
</tr>
<tr>
<td>Specific electric resistivity</td>
<td>$0.028 , \frac{\Omega.mm^2}{m}$</td>
</tr>
</tbody>
</table>

### Table B.2: Al-alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Major alloying element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>None: Al 99%</td>
</tr>
<tr>
<td>2xxx</td>
<td>Cu</td>
</tr>
<tr>
<td>3xxx</td>
<td>Mn</td>
</tr>
<tr>
<td>4xxx</td>
<td>Si</td>
</tr>
<tr>
<td>5xxx</td>
<td>Mg</td>
</tr>
<tr>
<td>6xxx</td>
<td>Mg + Si</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zn</td>
</tr>
<tr>
<td>8xxx</td>
<td>Other elements</td>
</tr>
</tbody>
</table>

Table B.1: Properties of Al

Table B.2: Al-alloys
Appendix C: Properties of titanium

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>22</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>$47.867 \frac{g}{mol}$</td>
</tr>
<tr>
<td>Density</td>
<td>$4.5 \frac{kg}{dm^3}$</td>
</tr>
<tr>
<td>Modulus of Young</td>
<td>$111000 \frac{N}{mm^2}$</td>
</tr>
<tr>
<td>Tensile stress</td>
<td>$350...560 \frac{N}{mm^2}$</td>
</tr>
<tr>
<td>Hardness</td>
<td>100...200 HB</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.36</td>
</tr>
<tr>
<td>Coefficient of linear expansion (0-100° C)</td>
<td>$8.2 \times 10^{-6} \frac{kJ}{K}$</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$0.63 \frac{kJ}{kg.K}$</td>
</tr>
<tr>
<td>Melting point</td>
<td>1660° C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$15.5 \frac{W}{m.K}$</td>
</tr>
<tr>
<td>Specific electric resistivity</td>
<td>$0.420 \frac{\Omega.mm^2}{m}$</td>
</tr>
</tbody>
</table>

Table C.1: Properties of Ti

<table>
<thead>
<tr>
<th>Grade</th>
<th>Major alloying element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>Commercially pure</td>
</tr>
<tr>
<td>5</td>
<td>6% Al + 4% V</td>
</tr>
<tr>
<td></td>
<td>Known as Ti6Al4V</td>
</tr>
<tr>
<td>6</td>
<td>5% Al + 2.5% Sn</td>
</tr>
<tr>
<td></td>
<td>Known as Ti-5Al-2.5Sn</td>
</tr>
</tbody>
</table>

Table C.2: Ti alloys